Evaluating Mobile Smartphone Application Security: The First Six Years

Professor *Patrick McDaniel*

Urbana-Champaign, IL

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A cautionary tale ...

2008 View : Security and smartphones

- 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

HOME HOUSE
20 Portman Square
London W1H 9HF

THE RESTAURANT
SRV 80 TABLE 123/1 TIME 22:55

1	HILDON	3.25
1	ARTI SOUP	5.95
1	TIGER PRAWNS	12.50
1	*********	0.00
1	BREAST OF DUCK	17.50
1	WELSH LAMB	18.75
1	DAUPHINOISE	2.75
1	ROAST PARSNIPS	2.75
1	HONORE DE BERTIC	19.50
2	PUDDING TROLLEY	11.90
1	Main Away	0.00
2	CAPPUCCINO	5.90
	SERVICE CHARGE	12.60

NET SALES 100.75 GRAND TOTAL 113.35

THIS IS NOT A VAT RECEIPT

VAT ANALYSIS

RATE %	NET	TAX	TOTAL
17.500	66.37	11.63	78.00
17.500	2.77	0.48	3.25
17.500	16.60	2.90	19.50

SIGNATURE:.....

PRINT NAME:.....

MEMBERSHIP No:.....

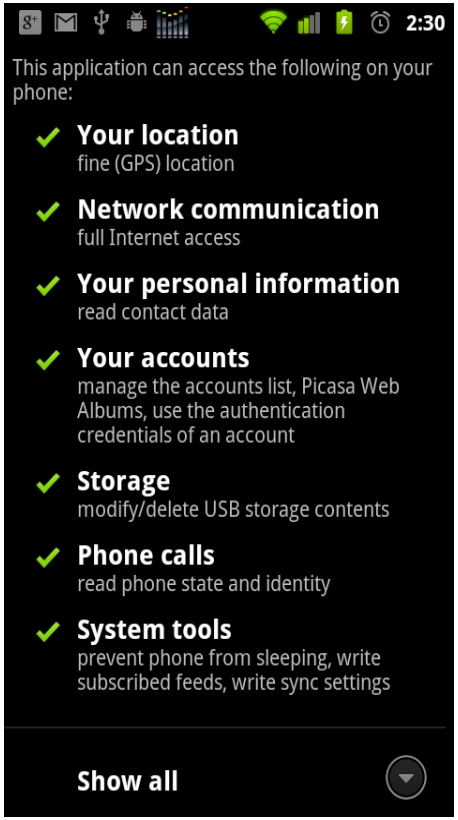
A DISCRETIONARY 12.5% SERVICE CHARGE
HAS BEEN ADDED TO YOUR ACCOUNT

Rethinking (host) Security

$$security == permissions \times apps$$

$$security \neq users$$

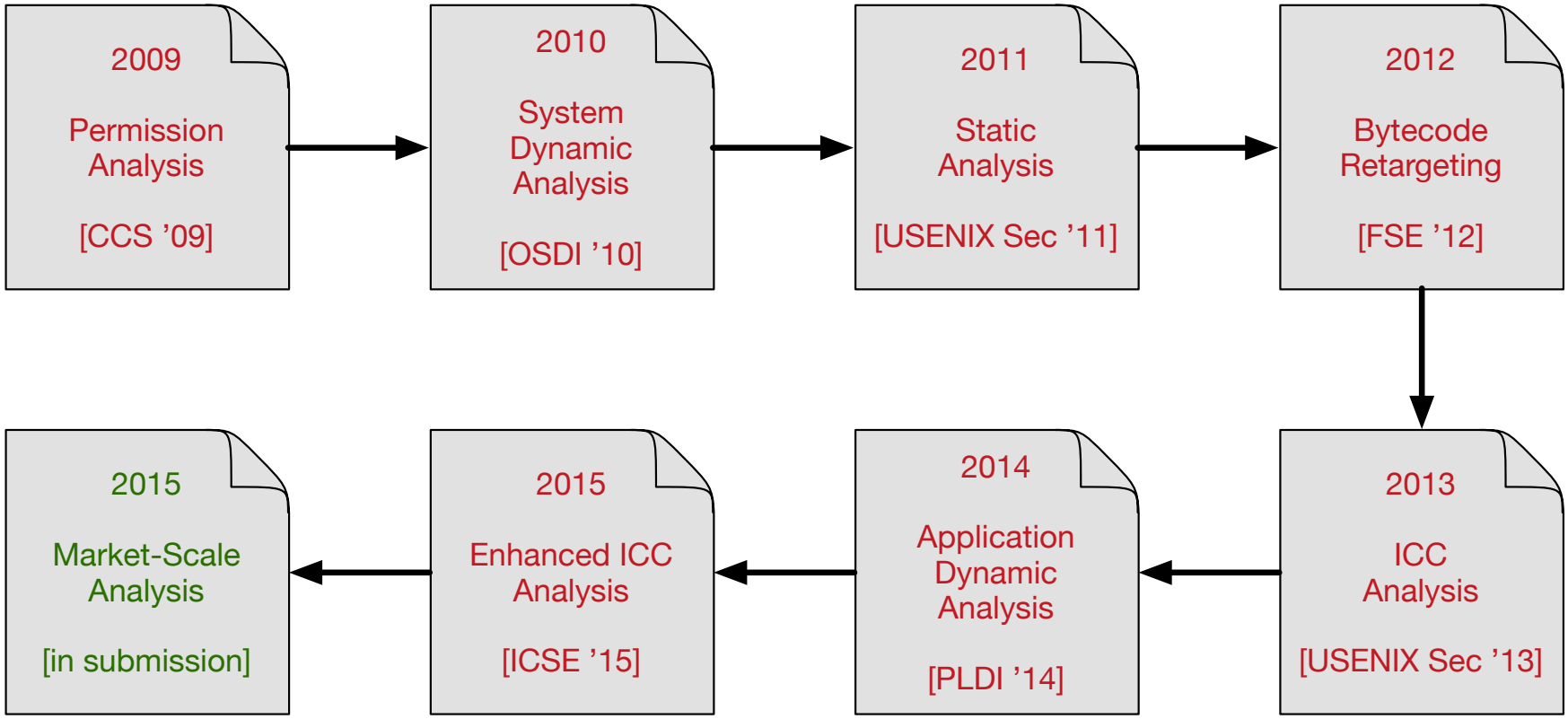
- *Permissions* define capabilities.
- *Application markets* deliver packaged *applications* *from* largely unknown sources.
- Users make permission decisions.
- Applications are run within middleware supported sandboxes provided by the OS.



- *Note*: App markets don't (and can't) provide security.

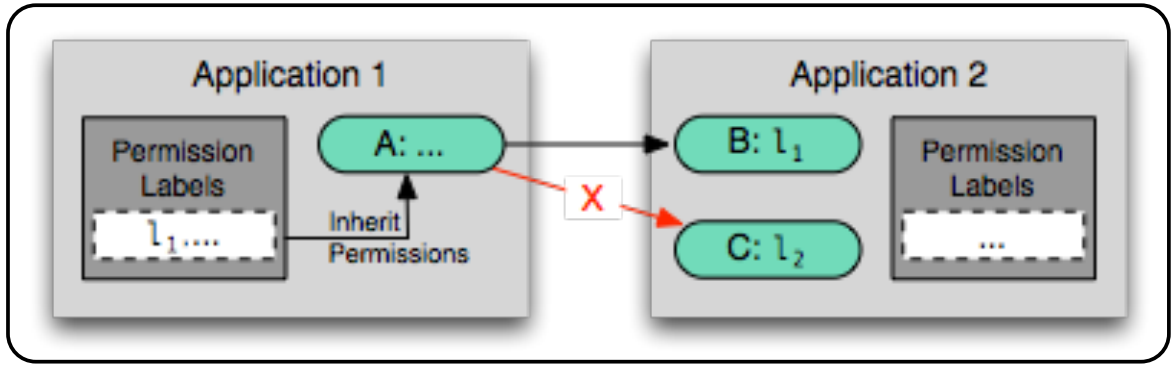
A 7-Year Span ...

- Evaluating Android Application Security ….



Example: Android Security

- Permissions granted to applications and *never* changed
  - Permissions allow an *application* to accesses 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"

William Enck, Machigar Ongtang, and Patrick McDaniel, *Understanding Android Security*. IEEE Security & Privacy Magazine, 7(1):50--57, January/February, 2009.

What do applications ask for?

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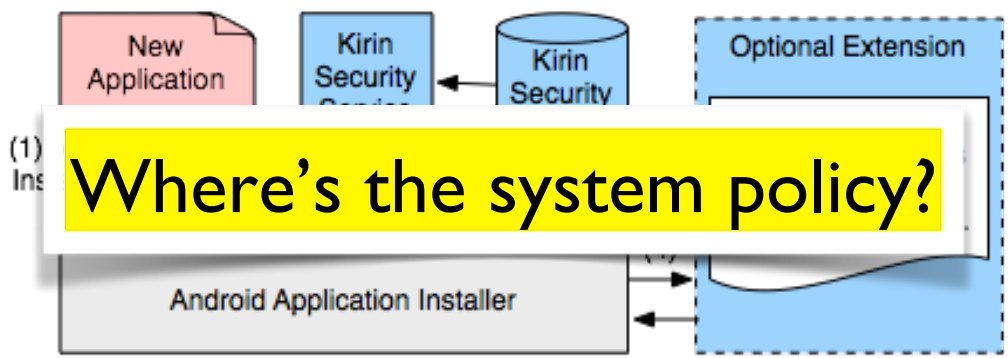
2009

- *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



William Enck, Machigar Ongtang, and Patrick McDaniel. On Lightweight Mobile Phone App Certification. *Proceedings of the 16th ACM Conference on Computer and Communications Security (CCS)*, pages 235-245, November 2009.

Kirin Security Policy

- Kirin enforces security invariants at install-time
  - Signatures of "malicious permission sets" approach
- Local evaluation of two manifest artifacts
  - The collection of requested permissions (*uses-permission*)
  - The types of registered Intent message listeners (i.e., sigs)
- Example:
  - Do not allow an application with Location and Internet permissions *and* receives the "booted" event

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

Policy Evaluation

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

- Policy evaluation is the satisfiability of invariants
  - Invariant violations found in O(n) w.r.t. policy size
- Model:
  - KSL rules are tuples: $r_i = (P_i, A_i)$
  - Configuration policy is a tuple: $c_t = (P_t, A_t)$
  - $fail(c_t, r_i)$ if $(P_t, A_t) = c_t, (P_i, A_i) = r_i, \boxed{P_i \subseteq P_t \wedge A_i \subseteq A_t}$
  - Certified if

$$F_R(c_t) = \{r_i | ri \in R, fail(c_t, r_i)\} = 0$$

Studying the (early) Market

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- Historical context
  - September 23, 2008 – Android released
  - Version 1.0, app market begins
- Evaluate 311* popular Market apps (Jan 2009)
  - 5 had both dangerous configuration and functionality (1.6%)
  - 5 dangerous configs, but plausable use of permisions (1.6%)

(1) *An applicatio*
(2) *An applicatio*
(3) *An applicatio* ns
(4) *An applicatio* *ermissions*
(5) *An applicatio* TE permissions
(6) *An applicatio*
(7) *An applicatio*
(8) *An applicatio*
(9) *An application must not have the SET_PREFERRED_APPLICATION permission and receive intents for the CALL action string*

3 apps failed -- (2) *An application must not have the* PHONE_STATE, RECORD _AUDIO, *and* INTERNET *permissions*

Q2: What do the applications do?

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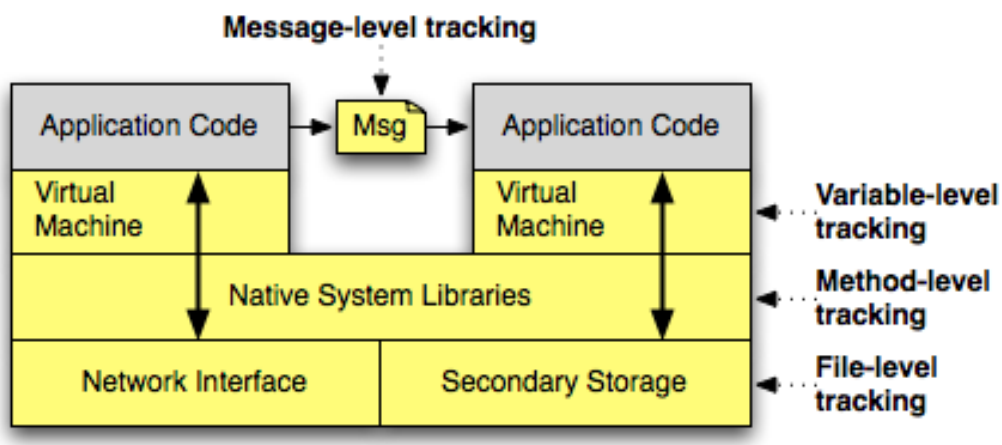
2010

- 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 invocation (JNI)
  3. *Binder IPC Layer*: extends tracking between applications
  4. *Storage Layer*: persistent tracking on files

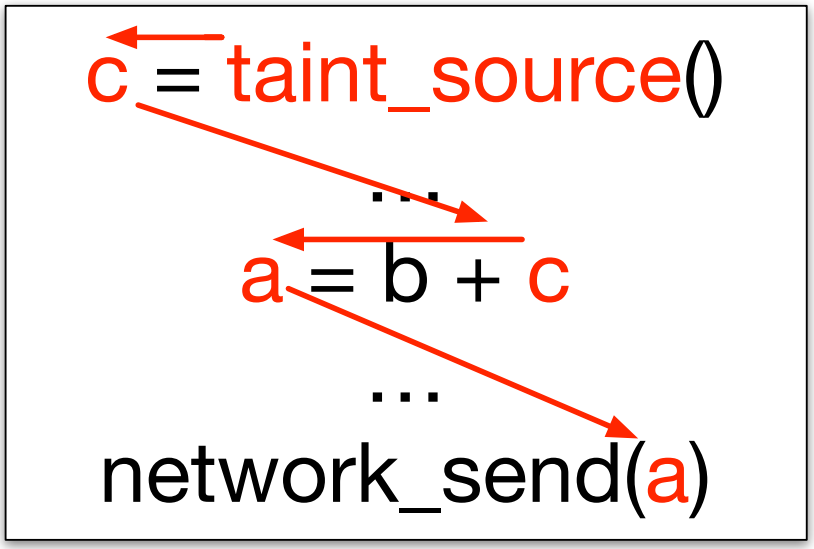


(Firmware mod)

William Enck, Peter Gilbert, Byung-Gon Chun, Landon P. Cox, Jaeyeon Jung, Patrick McDaniel, and Anmol N. Sheth, TaintDroid: An Information-Flow Tracking System for Realtime Privacy Monitoring on Smartphones. Communications of the ACM, 57(3), March, 2014.

Dynamic Taint Analysis

- Dynamic taint analysis is a technique that tracks information flow from an origin to output
- Conceptual idea:
  - Taint source
  - Taint propagation
  - Taint sink



- *Limitations*: performance and granularity is a trade-off

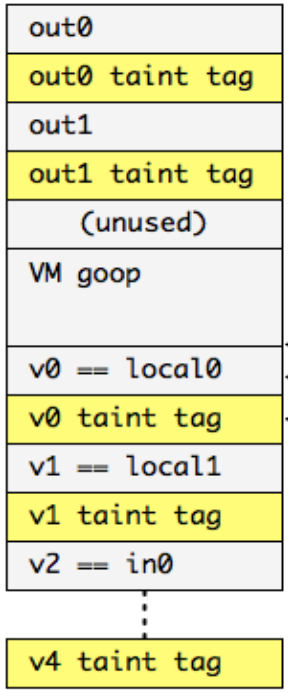
DEX Propagation Logic

- *Data flow*: propagate taints source regs to destination reg based on DEX (Dalvik executable) bytecode

Op Format	Op Semantics	Taint Propagation	Description
const-op v_A C	$v_A \leftarrow C$	$\tau(v_A) \leftarrow \emptyset$	Clear v_A taint
move-op v_A v_B	$v_A \leftarrow v_B$	$\tau(v_A) \leftarrow \tau(v_B)$	Set v_A taint to v_B taint
move-op-R v_A	$v_A \leftarrow R$	$\tau(v_A) \leftarrow \tau(R)$	Set v_A taint to return taint
return-op v_A	$R \leftarrow v_A$	$\tau(R) \leftarrow \tau(v_A)$	Set return taint ($\emptyset$ if void)
move-op-E v_A	$v_A \leftarrow E$	$\tau(v_A) \leftarrow \tau(E)$	Set v_A taint to exception taint
throw-op v_A	$E \leftarrow v_A$	$\tau(E) \leftarrow \tau(v_A)$	Set exception taint
unary-op v_A v_B	$v_A \leftarrow \otimes v_B$	$\tau(v_A) \leftarrow \tau(v_B)$	Set v_A taint to v_B taint
binary-op v_A v_B v_C	$v_A \leftarrow v_B \otimes v_C$	$\tau(v_A) \leftarrow \tau(v_B) \cup \tau(v_C)$	Set v_A taint to v_B taint $\cup$ v_C taint
binary-op v_A v_B	$v_A \leftarrow v_A \otimes v_B$	$\tau(v_A) \leftarrow \tau(v_A) \cup \tau(v_B)$	Update v_A taint with v_B taint
binary-op v_A v_B C	$v_A \leftarrow v_B \otimes C$	$\tau(v_A) \leftarrow \tau(v_B)$	Set v_A taint to v_B taint
aput-op v_A v_B v_C	$v_B[v_C] \leftarrow v_A$	$\tau(v_B[\cdot]) \leftarrow \tau(v_B[\cdot]) \cup \tau(v_A)$	Update array v_B taint with v_A taint
aget-op v_A v_B v_C	$v_A \leftarrow v_B[v_C]$	$\tau(v_A) \leftarrow \tau(v_B[\cdot]) \cup \tau(v_C)$	Set v_A taint to array and index taint
sput-op v_A f_B	$f_B \leftarrow v_A$	$\tau(f_B) \leftarrow \tau(v_A)$	Set field f_B taint to v_A taint
sget-op v_A f_B	$v_A \leftarrow f_B$	$\tau(v_A) \leftarrow \tau(f_B)$	Set v_A taint to field f_B taint
iput-op v_A v_B f_C	$v_B(f_C) \leftarrow v_A$	$\tau(v_B(f_C)) \leftarrow \tau(v_A)$	Set field f_C taint to v_A taint
iget-op v_A v_B f_C	$v_A \leftarrow v_B(f_C)$	$\tau(v_A) \leftarrow \tau(v_B(f_C)) \cup \tau(v_B)$	Set v_A taint to f_C and obj. ref. taint

VM Variable-level Tracking

- We modified the Dalvik VM interpreter to *store* and *propagate* taint tags (a taint bit-vector) on variables.
- *Local variables and args*: taint tags stored adjacent to variables on the internal execution stack.
  - 64-bit variables span 32-bit storage
- *Class fields*: similar to locals, but inside static and instance field heap objects
- *Arrays*: one taint tag per array to minimize overhead



Native Methods

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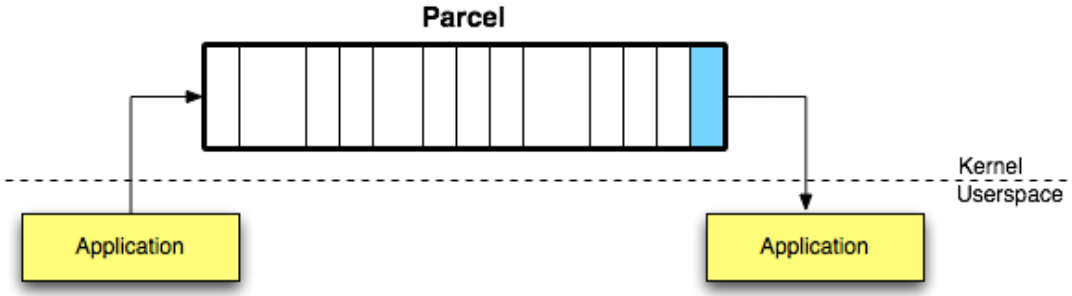
- Applications execute *native methods* through the Java Native Interface (JNI)
- TaintDroid uses a combination of heuristics and *method profiles* to patch VM tracking state
  - Applications are restricted to only invoking native methods in system-provided libraries
  - Survey showed 2,844 JNI methods included with OS.
  - Heuristic: return value taint gets union of input taints.
    - Leads to possibility of false positives.

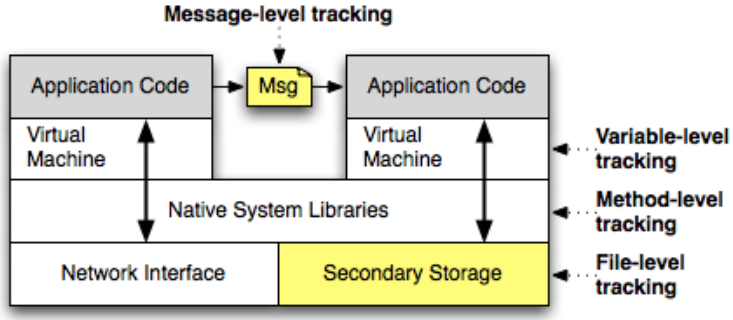
Note: accurately measuring information flow of JNI and Android APIs is an open problem.

IPC and File Propagation

- TaintDroid uses *message level* tracking for IPC
  - Applications marshall and unmarshall individual data items
  - Modify Binder IPC libraries to bundle taint tag



- Persistent storage tracked at the *file level*
  - Single taint tag stored in the file system XATTR
  - Add XATTR support to YAFFS2 and use ext2 for SDcard



Performance

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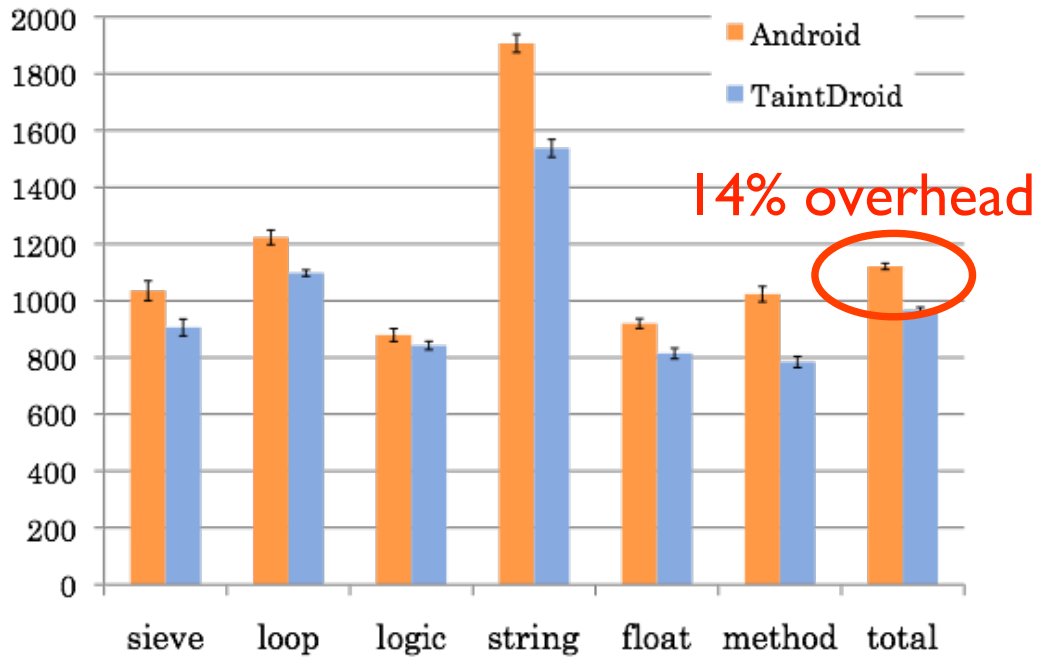
CaffeineMark 3.0 benchmark*

(higher is better)



- Memory overhead: 4.4%
- IPC overhead: 27%
- Macro-benchmark:
  - App load: 3% (2ms)
  - Address book: (< 20 ms) 5.5% create, 18% read
  - Phone call: 10% (10ms)
  - Take picture: 29% (0.5s)

*CaffeineMark score roughly corresponds to the number of Java instructions per second.

Application Study (2010)

- Selected 30 applications with bias on popularity and access to *Internet*, *location*, *microphone*, and *camera*

applications	#	permissions
The Weather Channel, Cetos, Solitarie, Movies, Babble, Manga Browser	6	
Bump, Wertago, Antivirus, ABC --- Animals, Traffic Jam, Hearts, Blackjack, Horoscope, 3001 Wisdom Quotes Lite, Yellow Pages, Datelefonbuch, Astrid, BBC News Live Stream, Ringtones	14	
Layer, Knocking, Coupons, Trapster, Spongebot Slide, ProBasketBall	6	
MySpace, Barcode Scanner, ixMAT	3	
Evernote	1	

- *Of 105 flagged connections, only 37 clearly legitimate*

Findings

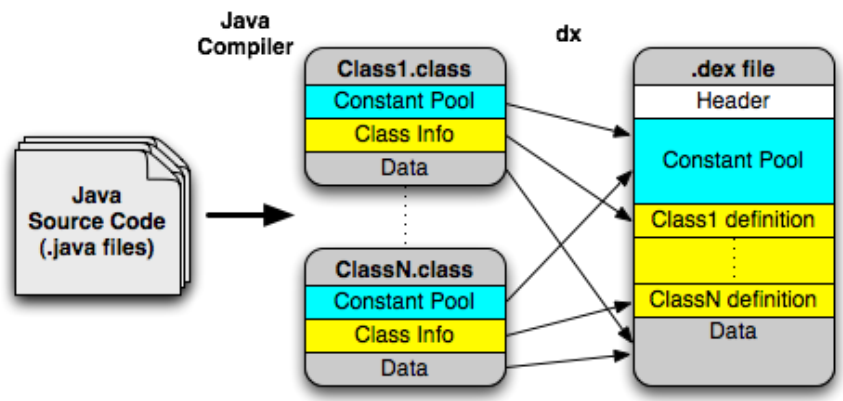
- 15 of the 30 applications shared physical location with an ad server (*admob.com*, *ad.qwapi.com*, *ads.mobclix.com*, *data.flurry.com*)
  - Most traffic was plaintext (e.g., AdMob HTTP GET):

```
...&s=a14a4a93f1e4c68&..&t=062A1CB1D476DE85
B717D9195A6722A9&d%5Bcoord%5D=47.6612278900
00006%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.

Aside: Dalvik EXecutables

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

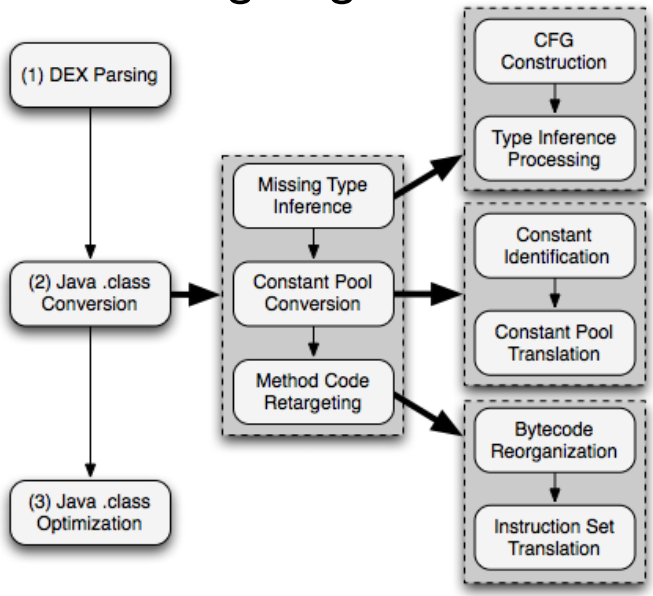


- We want to work with Java (bc), not DEX bytecode
  - There are a lot of existing program analysis tools for Java
  - We want to see what the developer was doing (i.e., confirmation)
- Non-trivial to retarget back to Java: *register vs. stack architecture*, *constant pools*, *ambiguous scalar types*, *null references*, etc.

Getting back to the Source

- The *ded* (later *dare*) decompiler
  - Refers to both the entire process and `.dex` ⇒ `.class` retargeting tool

Retargeting Process



- `ded/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)

2011

2012

DARE: Damien Octeau, Somesh Jha, and Patrick McDaniel. Retargeting Android Applications to Java Bytecode. *20th International Symposium on the Foundations of Software Engineering (FSE)*, November 2012. Research Triangle Park, NC. (**best artifact award**).

What can the applications do?

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2011

- *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?

William Enck, Damien Octeau, Patrick McDaniel, and Swarat Chaudhuri. A Study of Android Application Security. *Proceedings of the 20th USENIX Security Symposium*, August 2011. San Francisco, CA.

Studying Application Security

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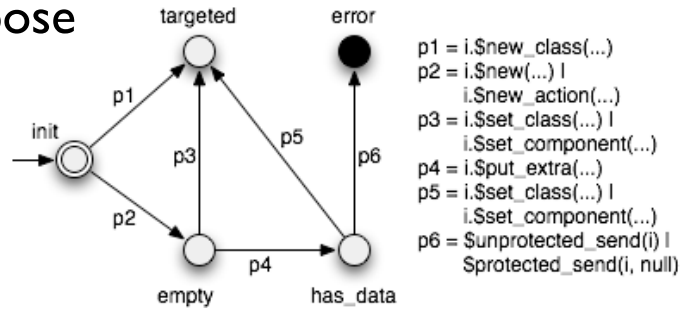
- Decompiled top 1,100 apps from Android market: over *21 MLOC*
- Queried for security properties using *program analysis*, followed by *manual inspection* to understand purpose
- Used several types of analysis to design security properties specific to Android using the Fortify SCA framework



Analysis for Dangerous Behavior

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
Havesting Installed Applications	Structural analysis

Also studied inclusion of advertisement and analytics libraries and associated properties

Analysis for Vulnerabilities

Leaking Information to Logs	Data flow analysis
Leaking Information to IPC	Control flow analysis
Unprotected Broadcast Receivers	Control flow analysis
Intent Injection Vulnerabilities	Control flow analysis
Delegation Vulnerabilities	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

Phone Identifiers

- Analysis pin-pointed *33 apps* leaking Phone IDs

com.avantar.wny - com/avantar/wny/PhoneStats.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;
}
```

IMEI

Tracking

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com.froogloid.kring.google.zxing.client.android - Activity_Router.java (Main Activity)

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

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

com.Qunar - net/NetworkTask.java

http://client.qunar.com:80/QSearch

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

Registration and Login

com.statefarm.pocketagent - activity/LogInActivity$1.java (Button callback)

IMEI

```
public void onClick(View  r1)
{
    ...
    r7 = Host.getDeviceId(this$0.getApplicationContext());
    LogInActivity.access$1(this$0).setUniqueDeviceID(r7);
    this$0.loginTask = new LogInActivity$LoginTask(this$0, null);
    this$0.showProgressDialog(r2, 2131361798, this$0.loginTask);
    r57 = this$0.loginTask;
    r58 = new LoginTO[1];
    r58[0] = LogInActivity.access$1(this$0);
    r57.execute(r58);
    ...
}
```

How would you feel about a PII to phone database?

Probing for Permissions

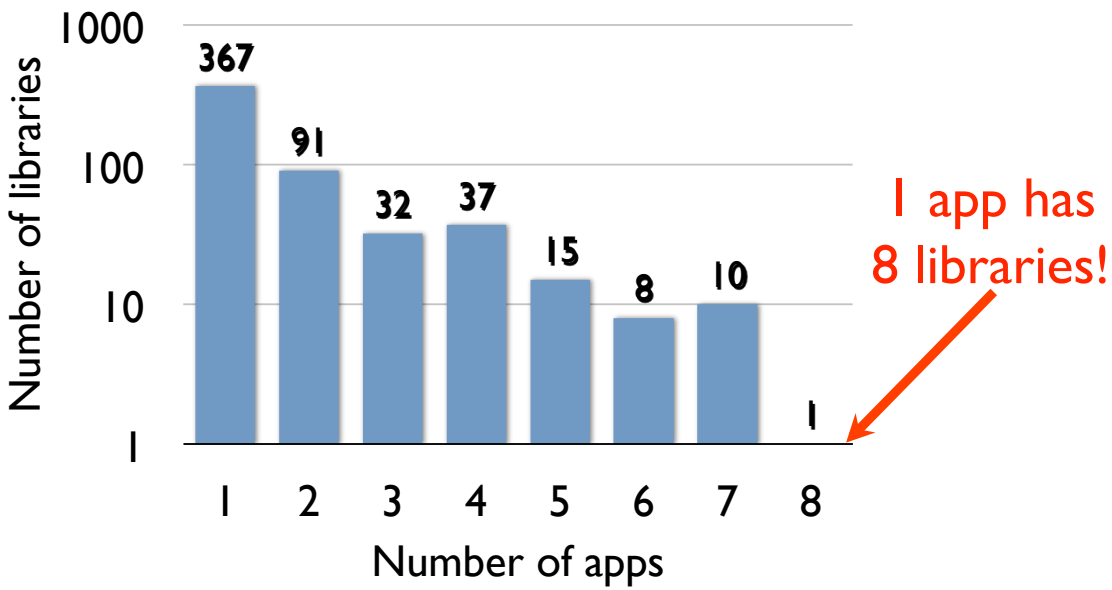
com/casee/adsdk/AdFetcher.java

```
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:

    ...
}
```

Checks before accessing

Ad/Analytics Libraries

- 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



Library Path	# Apps	Obtains
com/admob/android/ads	320	L
com/google/ads	206	-
com/flurry/android	98	-
com/qwapi/adclient/android	74	L, P, E
com/google/android/apps/analytics	67	-
com/adwhirl	60	L
com/mobclix/android/sdk	58	L, E
com/mellennialmedia/android	52	-
com/zestadz/android	10	-
com/admarvel/android/ads	8	-
com/estsoft/adlocal	8	L
com/adfonic/android	5	-
com/vdroid/ads	5	L, E
com/greystripe/android/sdk	4	E
com/medialets	4	L
com/wooboo/adlib_android	4	L, P, I
com/adserver/adview	3	L
com/tapjoy	3	-
com/inmobi/androidsdk	2	E
com/apegroup/ad	1	-
com/casee/adsdk	1	S
com/webtrents/mobile	1	L, E, S, I
Total Unique Apps	**561**	

L = Location; P = Ph#; E = IMEI; S = IMSI; I = ICC-ID

Intent Vulnerabilities

- 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

Data Flow (revisited)

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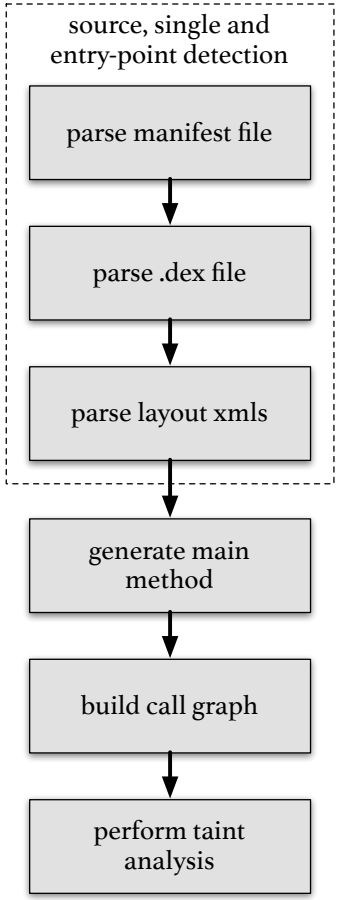
- Application analysis is more challenging because of application execution "life-cycle"
  - E.g., component asynchrony, multiple entry points, system events, callbacks …
- FlowDroid is a static taint analysis system that tracks data flow from sources to sinks
  - Approach: identify all entry points 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

2014



Steven Arzt, Siegfried Rasthofer, Christian Fritz, Eric Bodden, Alexandre Bartel, Jacques Klein, Yves Le Traon, Damien Octeau, and Patrick McDaniel. *FlowDroid: Precise Context, Flow, Field, Object-sensitive and Lifecycle-aware Taint Analysis for Android Apps*. Proc. of the 35th Programming Language Design and Implementation (PLDI), June 2014

How do applications work on concert?

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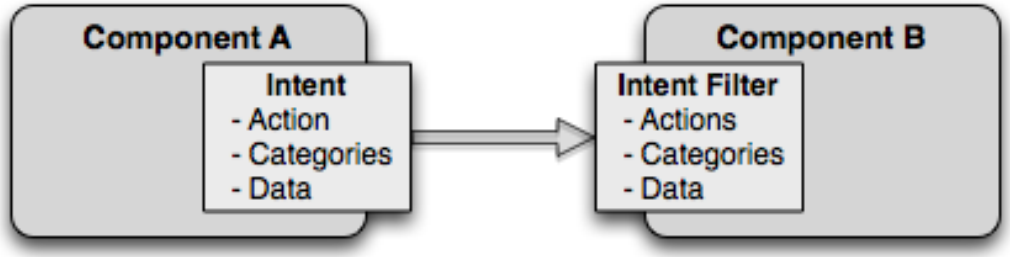
2013

- *Intents* are used to pass information between apps



- IPC (*intra-*) and component (*inter-application*) 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

Damien Octeau, Patrick McDaniel, Somesh Jha, Alexandre Bartel, Eric Bodden, Jacques Klein, and Yves Le Traon. Effective Inter-Component Communication Mapping in Android with Epicc: An Essential Step Towards Holistic Security Analysis.*Proceedings of the 22th USENIX Security Symposium*, August 2013. Washington, DC.

Analysis Results

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- 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: average113/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*

ICC Analysis version 2.0

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2015

- 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

Precision

	EPICC	IC3
Intents/Filters	69%	86%
URIs	34%	72%
Total	66%	85%

Identified (possible) ICC Flows

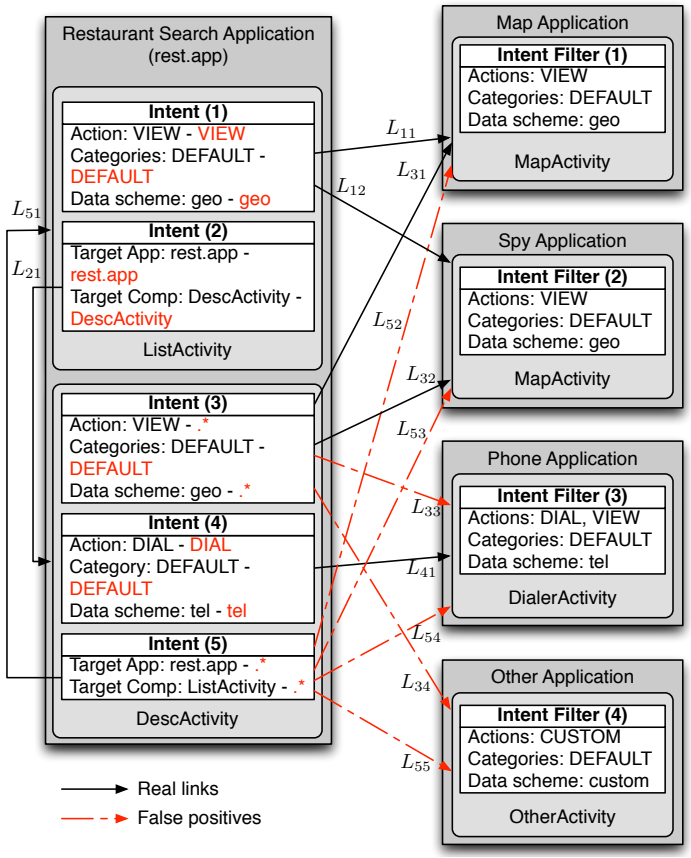
Epicc: 120,817
IC3: 26, 872

Damien Octeau, Daniel Luchaup, Matthew Dering, Somesh Jha, and Patrick McDaniel. Composite Constant Propagation: Application to Android Inter-Component Communication Analysis. Proceedings of the 37th International Conference on Software Engineering (ICSE), May 2015.

Ongoing: Scaling up analysis …

2015

- 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 $\mathcal{O}(e \cdot |I|)$, where e is small constant
- Experiment
  - Match 10,928 applications
  - Runtime: 8,434 seconds (140 min)

Intent
Application Name
Target Application
Target Component
Uses Permissions
Permission
Type
Action
Categories
Data

Intent Filter
Application Name
Component Name
Permission
Uses Permissions
Exported
Type
Actions
Categories
Data

2: Intent flow ranking

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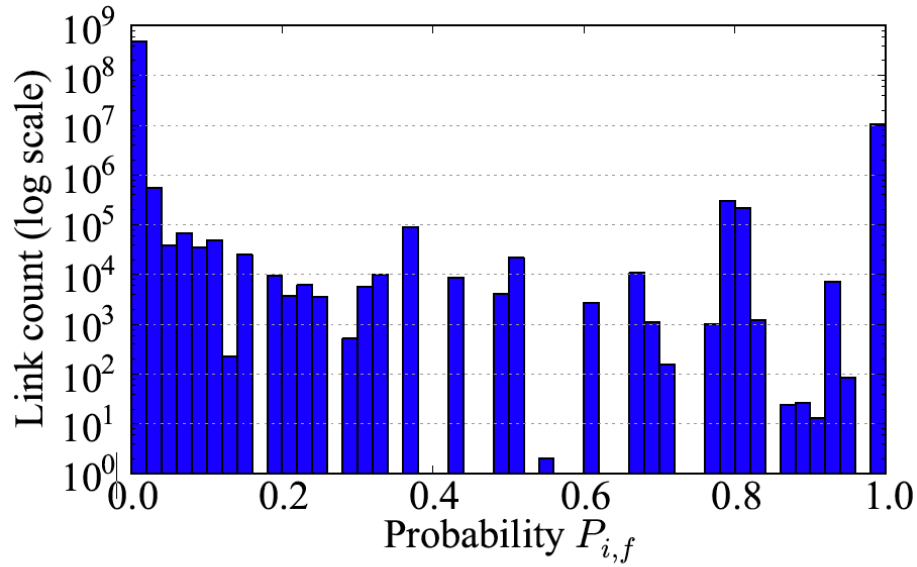
- Intent flow ranking – determining estimated likelihood of flows being "real" by comparing against known flows
- Idea: Intents are highly predictable
  - For example, displaying a map is done by sending Intent with VIEW action and geo scheme (common to applications)
  - Explicit Intents almost always 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(flow) = % 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



(a) Overall distribution of all probability values.

- 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!

Contact

Patrick McDaniel

mcdaniel@cse.psu.edu

http://siis.cse.psu.edu/

http://patrickmcdaniel.org/