Collaborative Verification of Information Flow for a High-Assurance App Store

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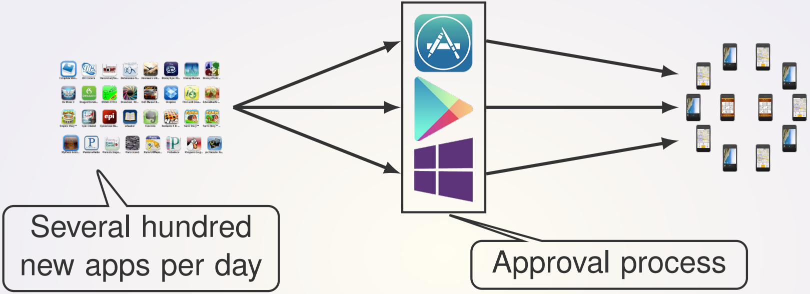
Current commercial app stores



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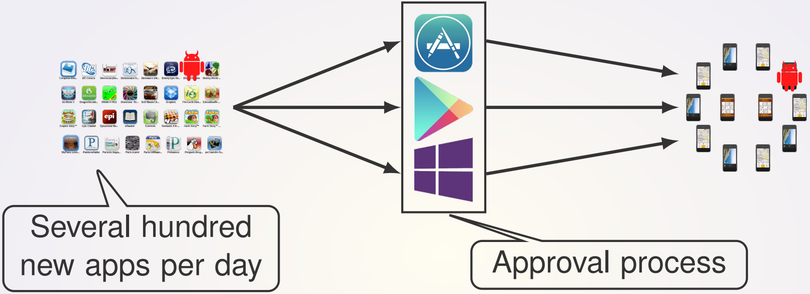

Problem: Every major app store has approved malware!

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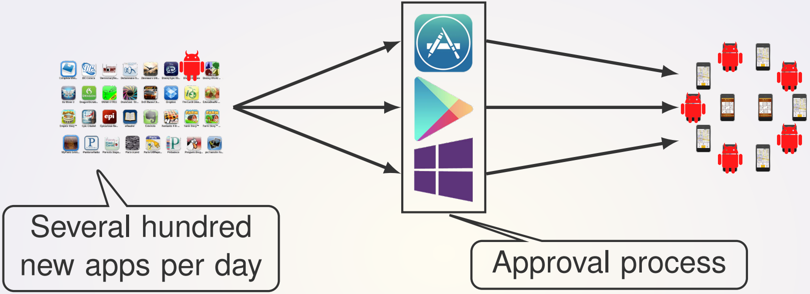

Problem: Every major app store has approved malware!

Best effort solution: Malware removed when encountered

High-assurance app stores

Needed in multiple domains

- Government app stores (e.g., DoD)
- Corporate app stores (e.g., financial sector)
- App stores for medical apps

Require stronger guarantees

- Verified **absence of** (certain types of) **malware**

Verification is costly

- Effort is solely on app store side
- Analyst needs to understand/reverse-engineer the app

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Our solution: Collaboratively verify absence of malware

Our focus: Information-flow malware

Example: Information-flow malware

App

Sudoku

Permissions

Read location
Internet

Example: Information-flow malware

App

Sudoku

Permissions

Read location

Internet

Example: Information-flow malware

App	Permissions
 Sudoku	Read location Internet
 Camera	Read location Internet

Example: Information-flow malware

App	Permissions
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Example: Information-flow malware

App	Permissions	Information flow
 Sudoku	Read location Internet	
 Camera	Read location Internet	Location → Internet

Example: Information-flow malware

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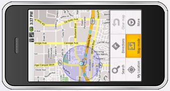 Map	Read location Internet	

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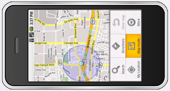 Map	Read location Internet	

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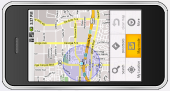 Map	Read location Internet	Location → Internet

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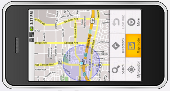 Map	Read location Internet	Location → Internet

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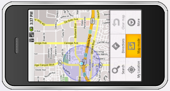 Map	Read location Internet	Location → Internet	Location → BadGuy.com

Example: Information-flow malware

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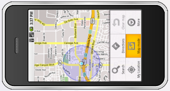
 Sudoku	**Read location** **Internet**		
 Camera	**Read location** **Internet**	**Location → Internet**	
 Map	**Read location** **Internet**	**Location → Internet**	**Location → BadGuy.com**

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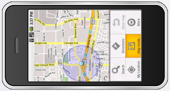
 Map	Read location Internet	Location → Internet	Location → BadGuy.com

Prevent malware using an information flow type-system

Approach: Overview

Collaborative verification model

- Leverage but don't trust the developer

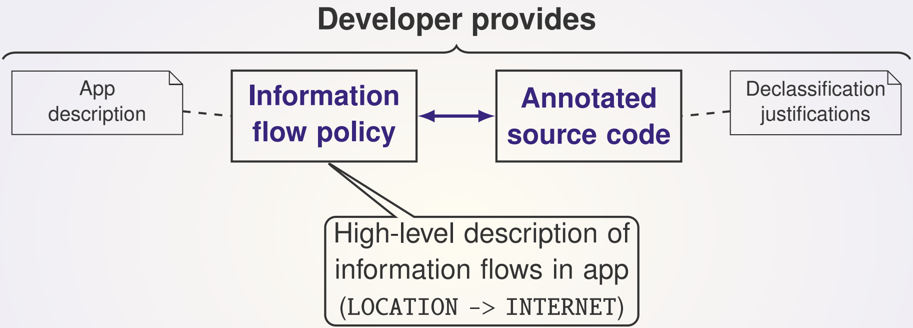
Information Flow Type-checker (IFT)

- Finer-grained permission model for Android
- False positives and declassifications
- Implicit information flow

Evaluation

- Effectiveness: Effective for real malware in real apps
- Usability: Low annotation and auditing burden

Collaborative verification model



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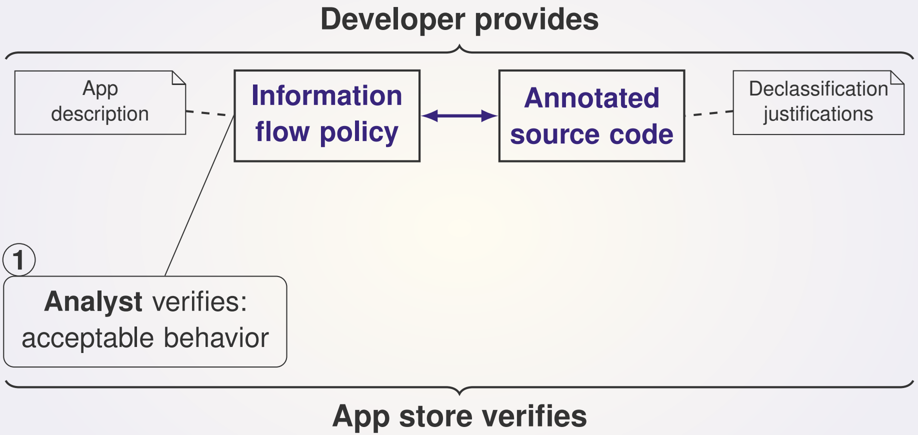

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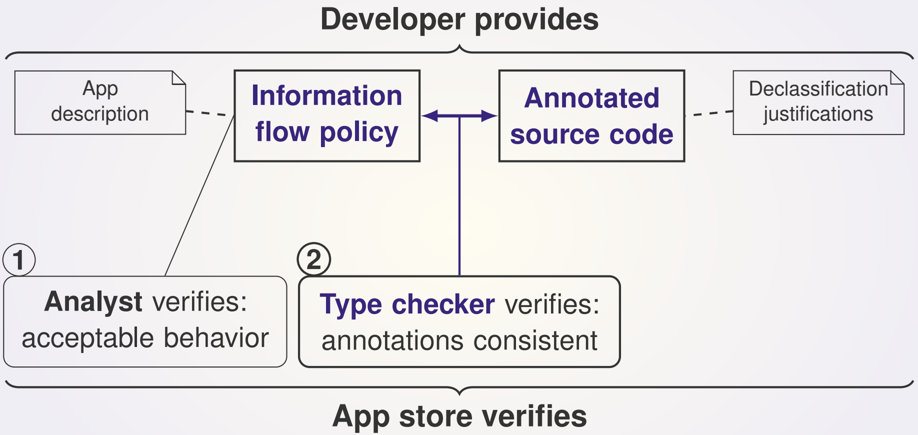

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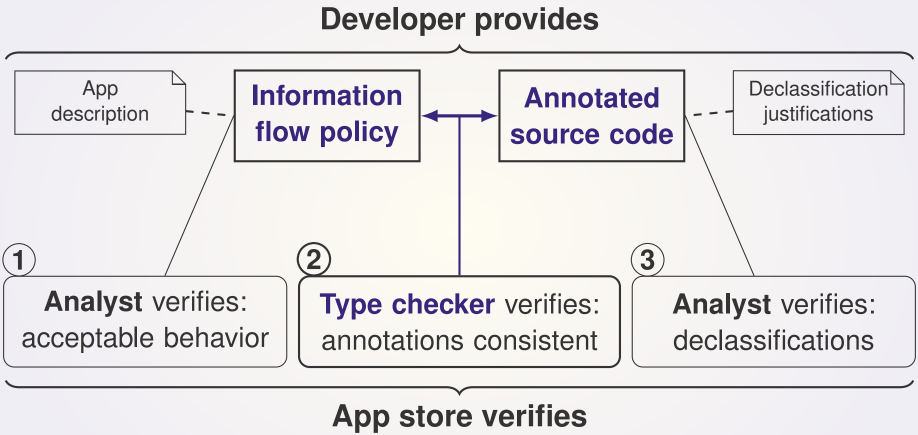

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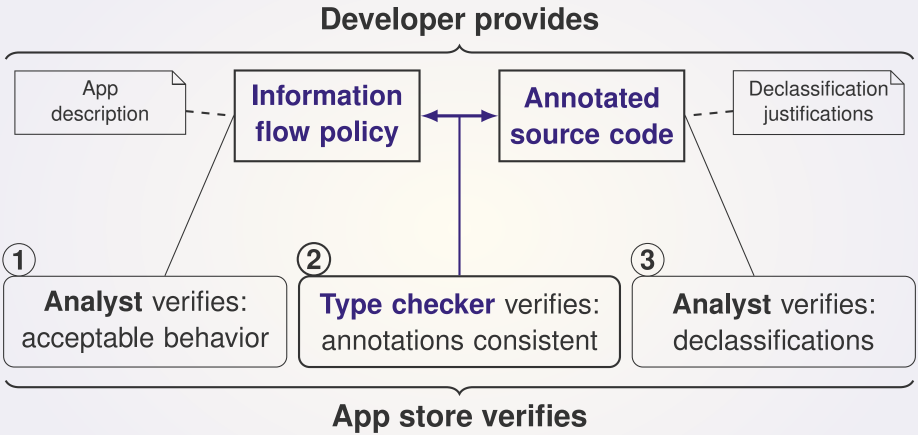
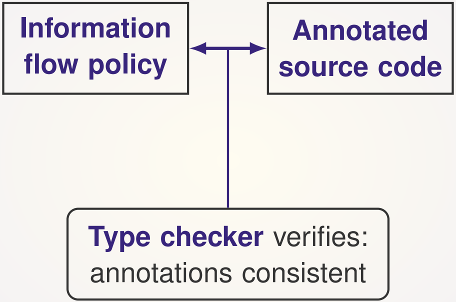


Developer and analyst do tasks that are easy for them

Verification of information flow



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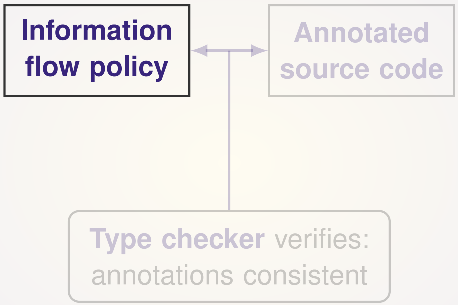

Information flow policy

High-level description of permitted information flows

```
READ_SMS               ->   INTERNET
READ_CLIPBOARD         ->   DISPLAY
USER_INPUT             ->   CALL_PHONE
ACCESS_FINE_LOCATION   ->   INTERNET(maps.google.com)
```

Information flow policy

High-level description of permitted information flows

Source	flows to	Sink
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Sources and Sinks

- **Default Android permissions (145)**

Not sufficient to model information flow!

Information flow policy

High-level description of permitted information flows

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Sources and Sinks

- Default Android permissions (145)
- **Additional sensitive resources (28)**

Information flow policy

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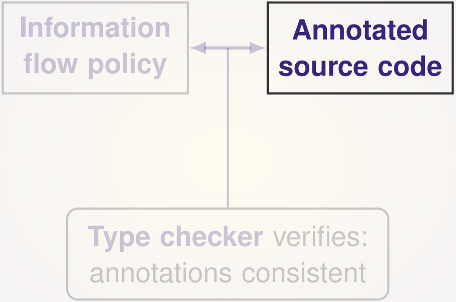
`ACCESS_FINE_LOCATION`	`->`	**`INTERNET(maps.google.com)`**

Sources and Sinks

- Default Android permissions (145)
- Additional sensitive resources (28)
- **Parameterized permissions**

Verification of information flow



Information flow types: Sources and Sinks

@Source Where might a value come from?

@Sink Where might a value flow to?

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Android API

```
void sendToInternet(String message);
String readGPS();
```

Information flow types: Sources and Sinks

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To Internet

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Information flow types: Sources and Sinks

@Source Where might a value come from?
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Android API

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void sendToInternet(@Sink(INTERNET)String message);
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void sendToInternet(@Sink(INTERNET)String message);
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From Location

Information flow types: Sources and Sinks

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App code

```
String loc = readGPS();
sendToInternet(loc);
```

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Information flow types: Sources and Sinks

@Source Where might a value come from?
@Sink Where might a value flow to?

Android API

API annotations are pre-verified

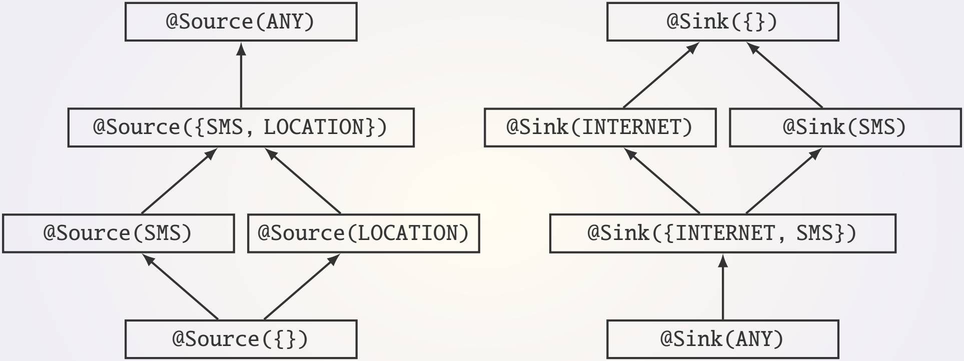
```
void sendToInternet(@Sink(INTERNET)String message);
@Source(LOCATION)String readGPS();
```

App code

Developer annotations are not trusted

```
@Source(LOCATION)@Sink(INTERNET)String loc = readGPS();
sendToInternet(loc);
```

Type hierarchy for Sources and Sinks



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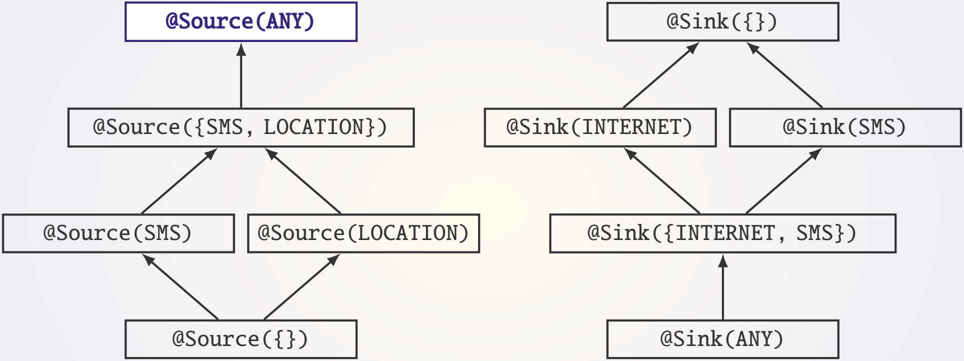
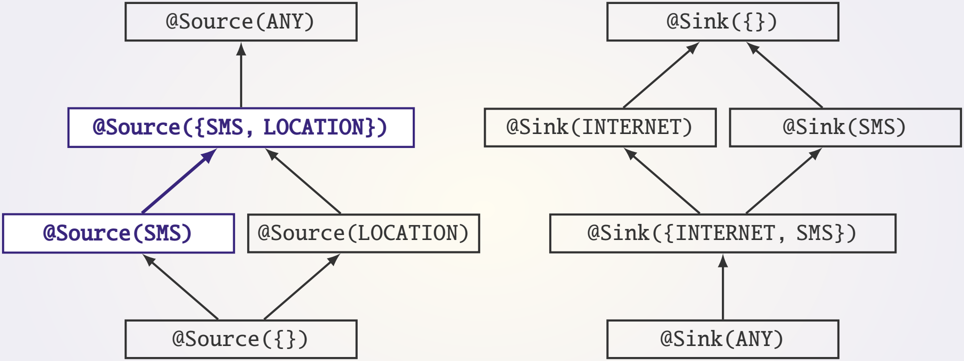


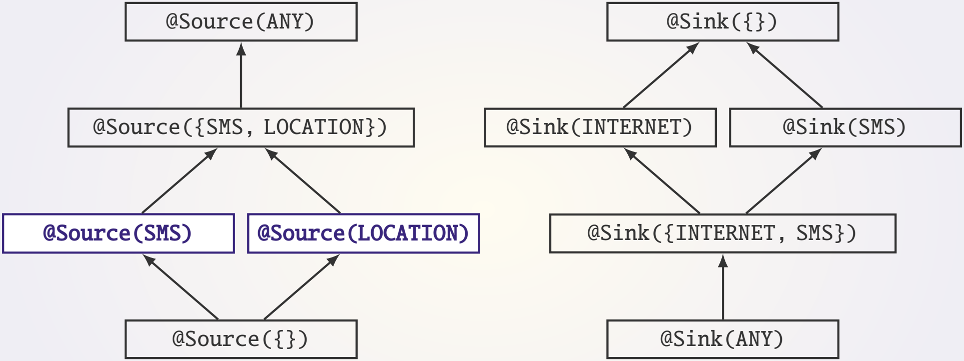
@Source(ANY) ≡ @Source({SMS, LOCATION, INTERNET, ...})

Type hierarchy for Sources and Sinks




```
@Source(SMS)String sms = ...;
@Source({SMS, LOCATION})String smsLoc = sms;
```

Type hierarchy for Sources and Sinks

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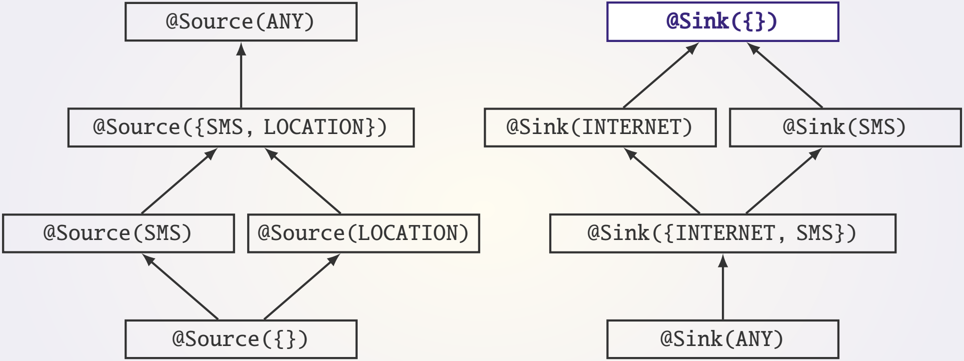

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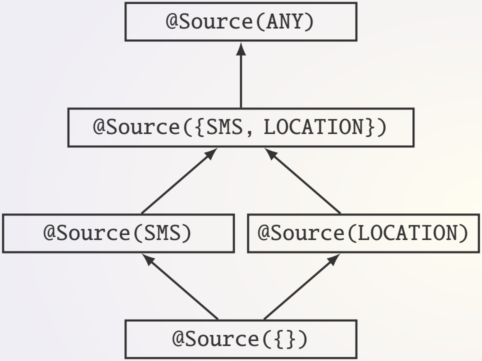
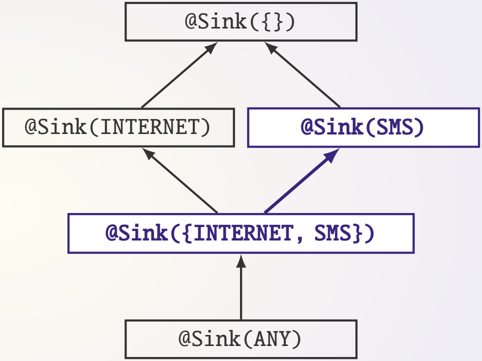
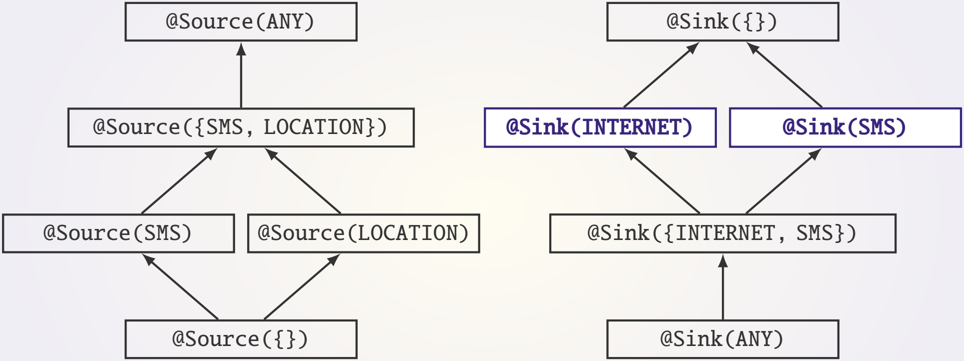





```
@Sink({INTERNET, SMS})String toInetSms;
@Sink(SMS)String toSms = toInetSms;
```

Type hierarchy for Sources and Sinks

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@Sink(SMS)String toSms;
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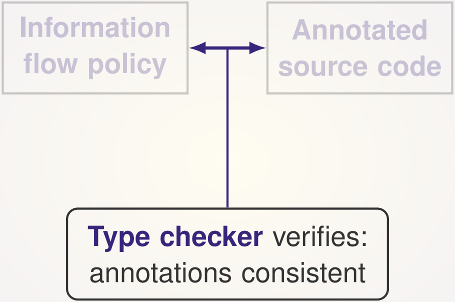
Verification of information flow



Information Flow Type-checker (IFT): Overview

Guarantees of type-checking

1. Annotations are consistent with code (type correctness)
2. Annotations are consistent with flow policy

Type checker verifies:
annotations consistent

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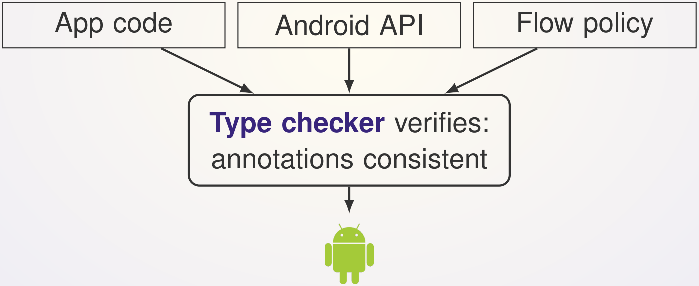

No undisclosed information flows in app

Information Flow Type-checker (IFT): Example

App code

```
@Source(LOCATION)@Sink(INTERNET)String loc = readGPS();
sendToInternet(loc);
```

Flow policy

```
LOCATION -> INTERNET
```

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Information Flow Type-checker (IFT): Example

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Incompatible sinks:
INTERNET $\not<:$ SMS

Information Flow Type-checker (IFT): Example

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Flow policy

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```

Flow policy

```
LOCATION -> INTERNET
```

Type checker verifies:
annotations consistent

Forbidden flow:
LOCATION -> SMS

False positives and declassifications

App code

```
@Source({LOCATION, SMS})String[] array;
array[0] = readGPS();
array[1] = readSMS();

@Source(LOCATION)String loc = array[0];
```

False positives and declassifications

App code

```
@Source({LOCATION, SMS})String[] array;
array[0] = readGPS();
array[1] = readSMS();        @Source(LOCATION)

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@Source({LOCATION, SMS})String[] array;
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```

@Source(LOCATION)

@Source(LOCATION, SMS)

False positives and declassifications

App code

```
@Source({LOCATION, SMS})String[] array;
array[0] = readGPS();
array[1] = readSMS();
@SuppressWarnings("flow") // Always returns location data
@Source(LOCATION)String loc = array[0];
```

Declassifications

- Developer can **suppress false-positive** warnings
- App store **employee verifies** each **declassification**

Reducing false positives

Flow sensitivity

- Type refinement with intra-procedural data flow analysis

App code

```
@Source({LOCATION, SMS})String value;
if (...) {
 value = readSMS();
 ... value: @Source(SMS)
}
... value: @Source({LOCATION, SMS})
```

Reducing false positives

Flow sensitivity

- Type refinement with intra-procedural data flow analysis

Context sensitivity

- Polymorphism (e.g., String operations, I/O streams, etc.)

App code

```
@Source({LOCATION, SMS})String value = ...;
String substring = value.substring(0,8);
```

Returns `@Source({LOCATION, SMS})`

Reducing false positives

Flow sensitivity

- Type refinement with intra-procedural data flow analysis

Context sensitivity

- Polymorphism (e.g., String operations, I/O streams, etc.)

Indirect control flow

- Constant value propagation
- Reflection analysis
- Intent analysis

Implicit information flow

App code

```
@Source(USER_INPUT)long creditCard = getCard();
long i=0;
while (true) {
  if (++i == creditCard) {
    sendToInternet(i);
  }
}
```

Implicit information flow

App code

```
@Source(USER_INPUT)long creditCard = getCard();
long i=0;
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  }
}
```

Card number implicitly leaked

Classic approach (*Denning and Denning, CACM'77*)

- Taint all computations in dynamic scope
- Over-tainting may lead to taint explosion

Implicit information flow

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USER_INPUT -> CONDITIONAL

Our approach: Prune irrelevant conditions

- Add additional Sink CONDITIONAL
- Type-checking warning for conditions with sensitive Source

Implicit information flow

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USER_INPUT -> CONDITIONAL

Our approach: Prune irrelevant conditions

- Add additional Sink `CONDITIONAL`
- Type-checking warning for conditions with sensitive Source
- Analyst is aware of context
- No need to analyze dynamic scope for irrelevant conditions (e.g., null checks, malicious conditions, or trigger)

Evaluation: Overview

Are our permission model and type system effective?

- Adversarial red team challenge
- Evaluation of effectiveness for real malware

Is our approach effective and efficient in a time-constrained set up?

- Control team study
- Comparison of effectiveness and efficiency to control team

Is our verification model applicable for real-world apps?

- Usability study with annotators and auditors
- Evaluation of annotation and auditing burden

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Apps are not pre-annotated

Adversarial red team challenge

Setup

- 5 independent red teams
- 72 Android apps (47 malicious — information-flow malware)
- 8,000 LOC and 12 permissions on average

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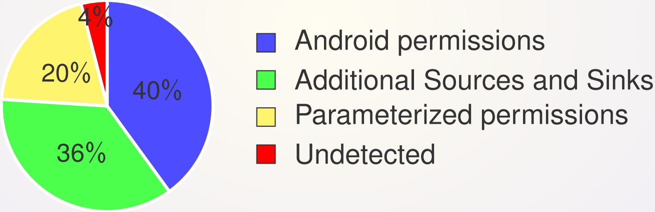
Results for 47 malicious apps



- **96%** overall **detection** rate — **4%** require modeling of information flow paths (`LOCATION -> ENCRYPT -> INTERNET`)
- **60%** of apps require our **finer-grained sources and sinks**

Control team study

Setup

- Control team using dynamic and static analysis tools
- 18 Android apps (13 malicious)
- 7,000 LOC and 16 permissions on average

Control team study

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Results

Usability study

Setup

- 2 groups acting as annotators and auditors
- 11 Android apps (1 malicious)
- 900 LOC and 12 permissions on average

Usability study

Setup

- 2 groups acting as annotators and auditors
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Annotation burden

- 96% of type annotations are inferred
- Annotations required: 6 per 100 lines of code
- Annotation time: 16 minutes per 100 lines of code

Most time spent on reverse engineering

Usability study cont.

Declassifications

- 50% of apps had no declassifications
- On average 3 declassification per 1,000 lines of code

IFT's features effectively reduce false positives

Usability study cont.

Declassifications

- 50% of apps had no declassifications
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IFT's features effectively reduce false positives

Auditing burden

- Overall review time: 3 minutes per 100 lines of code
- 35% of time: review the flow policy
- 65% of time: review declassifications & conditionals

Only 23% of conditionals needed to be reviewed

Related work: Information flow

Jif ***(Myers, POPL'99)***

- A security-typed language (incompatible Java extension)
- Supports dynamic checks and focuses on expressiveness

FlowDroid ***(Arzt et al., PLDI'14)*****, SuSi** ***(Rasthofer et al., NDSS'14)***

- FlowDroid propagates sources and sinks found by SuSi
- SuSi classifies Android API methods using machine learning

IFT makes static verification of Android apps practical

- **Finer-grained sources and sinks at type level**
- **Compiler plug-in using standard Java type annotations**

Related work: Collaborative verification model

Verifying browser extensions

- IBEX *(Guha et al., S&P'11)*
  - Verification of Fine (ML dialect) against complex policies
- *Lerner et al., ESORICS'13*
  - Verification of private browsing using annotated JavaScript

IFT verifies information flow in Android apps using a high-level flow policy

Automated policy verification

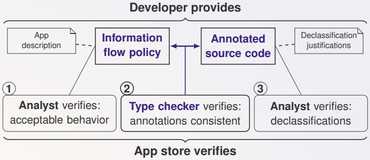
- Crowd-sourcing *(Agarwal & Hall, MobiSys'13)*
- Natural language processing *(Pandita et al., USENIX'13)*
- Clustering *(Gorla et al., ICSE'14)*.

Could aid manual verification of flow policies

Conclusions

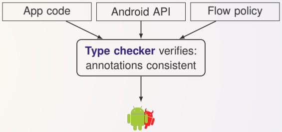
Collaborative verification model

- Low overall verification effort for developer and app store analyst
- IFT combined with other analyses



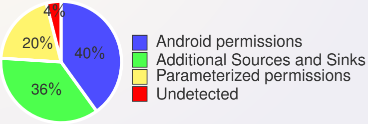
Information Flow Type-checker (IFT)

- Context and flow-sensitive type system
- Fine-grained model for sources and sinks
- High-level information flow policy



Evaluation

- Detected 96% information-flow malware
- Low annotation and auditing burden
- Low false-positive rate



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