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

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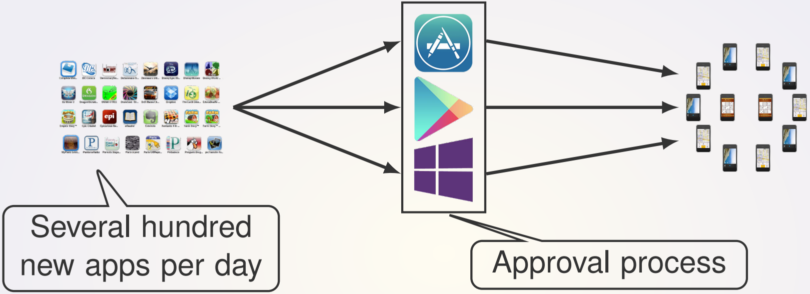
November 6, 2014

# Current commercial app stores



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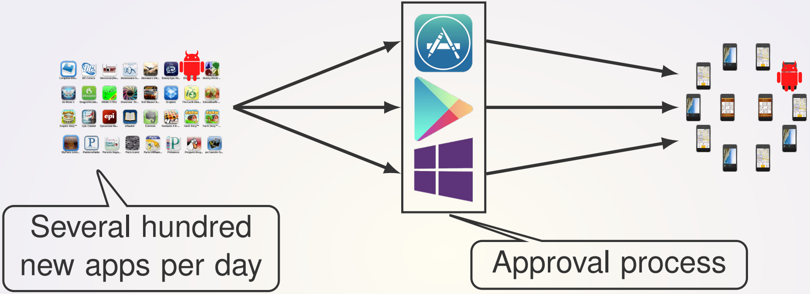


**Problem: Every major app store has approved malware!**

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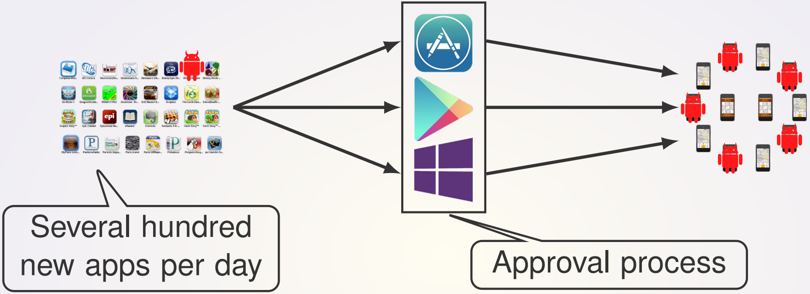


**Problem: Every major app store has approved malware!**

**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**

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Sudoku

**Permissions**

**Read location**

**Internet** 

# Example: Information-flow malware

| App | Permissions |
|---|---|
|  Sudoku | Read location<br>Internet  |
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|  Sudoku | **Read location** **Internet** | |
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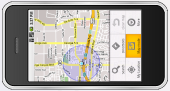
|  Map | Read location<br>Internet | |

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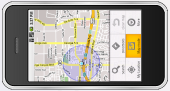
|  Map | Read location<br>Internet | |

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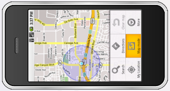
|  Map | Read location<br>Internet | Location →<br>Internet |

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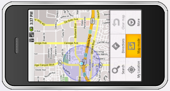
|  Map | Read location<br>Internet  | Location →<br>Internet  |

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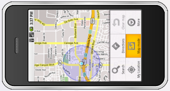
|  Map | Read location Internet | Location → Internet | Location → BadGuy.com |

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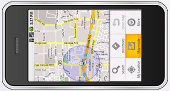
|  Map | Read location Internet | Location → Internet | Location → BadGuy.com |

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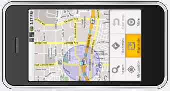
|  Map | Read location<br>Internet | Location →<br>Internet | Location →<br>BadGuy.com |

**Prevent malware using an information flow type-system**

# Approach: Overview

**Collaborative verification model**

- Leverage but don't trust the developer

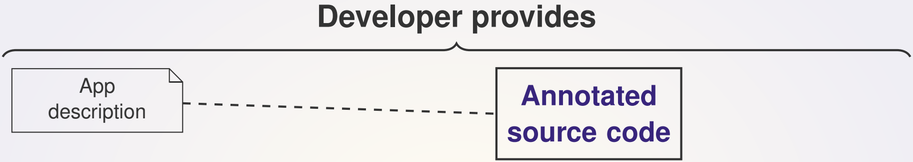
**Information Flow Type-checker (IFT)**

- 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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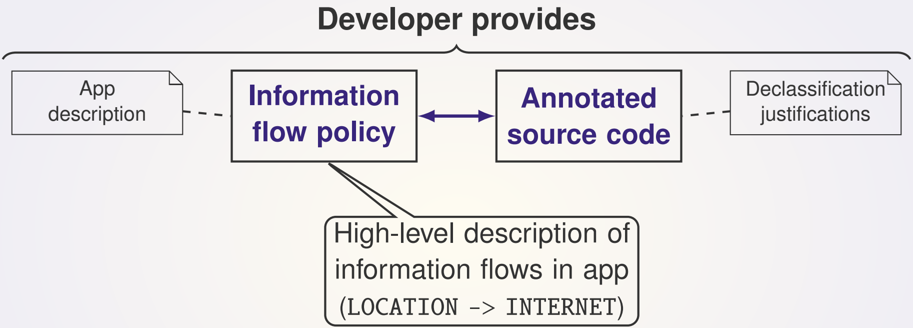

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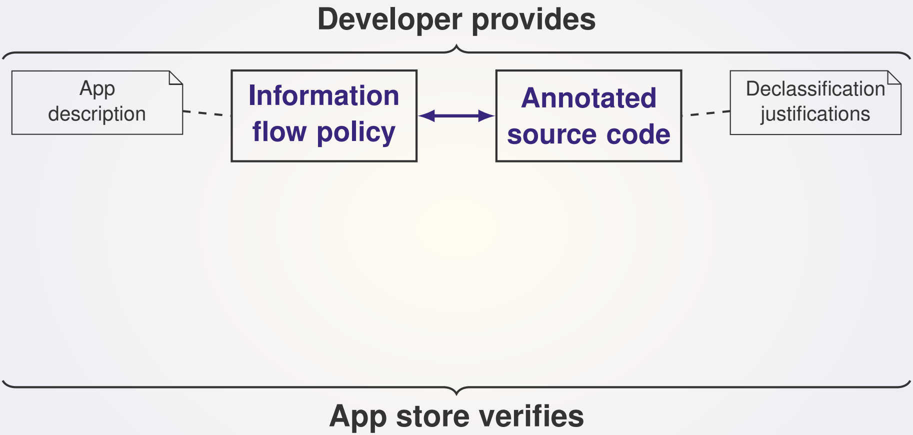

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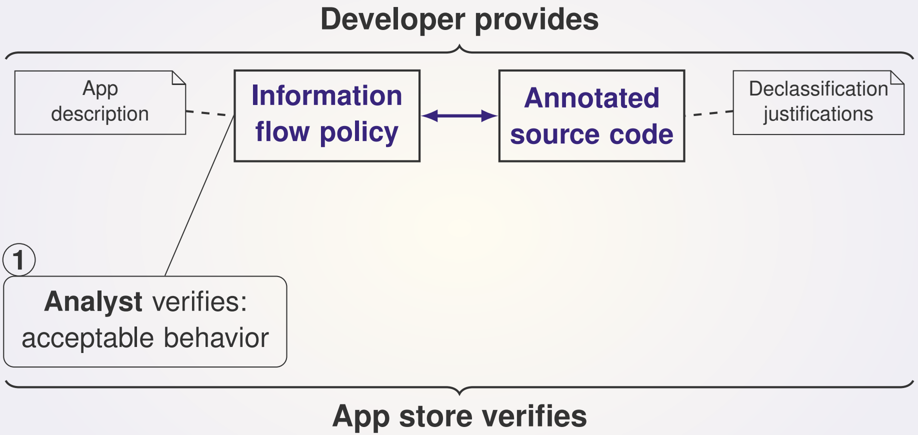

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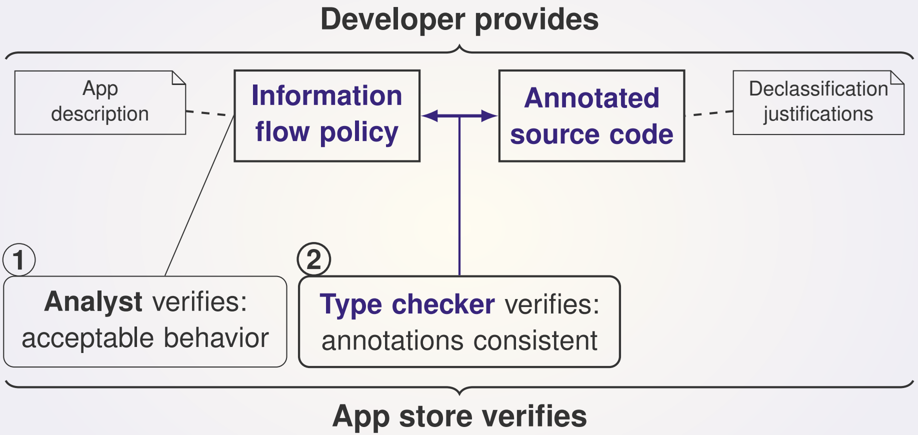

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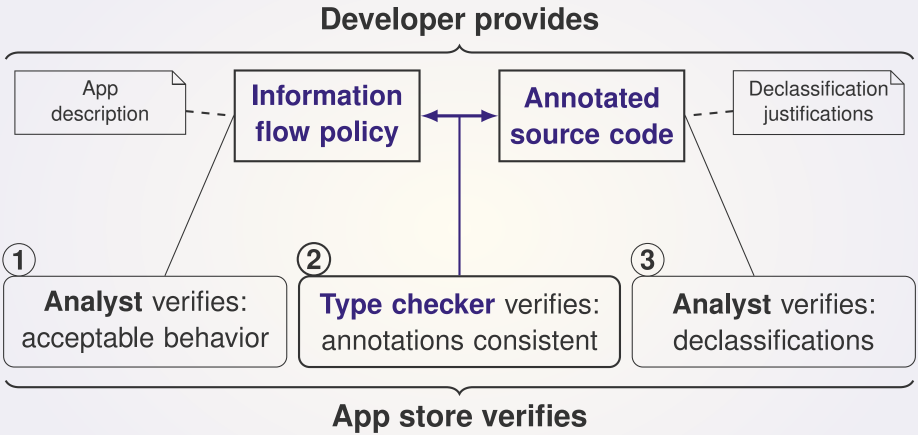

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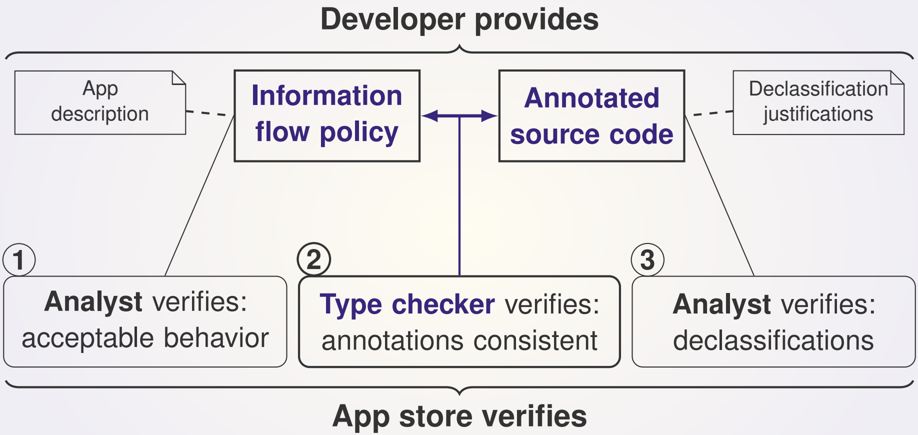
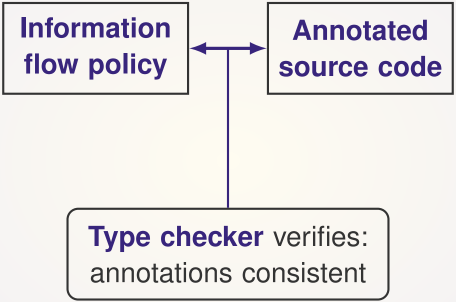



**Developer and analyst do tasks that are easy for them**

# Verification of information flow



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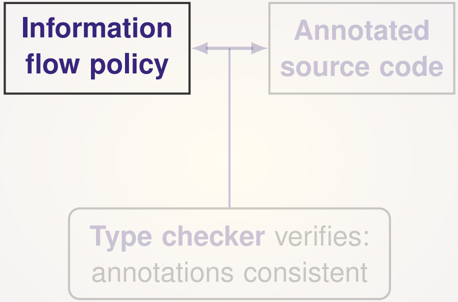

# Information flow policy

**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

| $\overbrace{\text{READ\_SMS}}^{\textbf{Source}}$ | $\overbrace{\text{->}}^{\textbf{flows to}}$ | $\overbrace{\text{INTERNET}}^{\textbf{Sink}}$ |
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## Sources and Sinks

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

# Information flow policy

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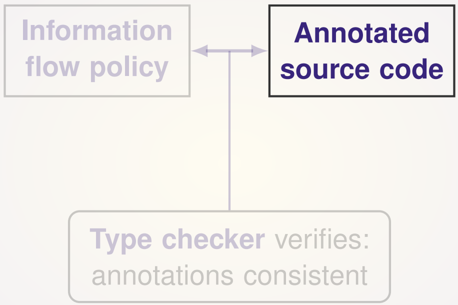
- Default Android permissions (145)
- Additional sensitive resources (28)
- **Parameterized permissions**

# Verification of information flow



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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();
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```
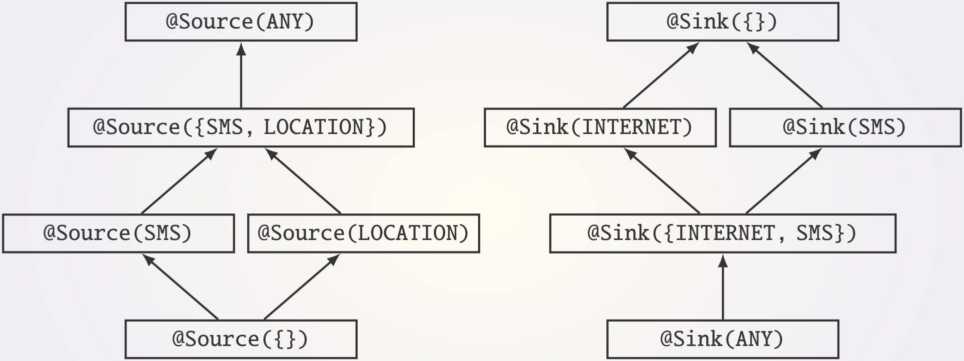

# Type hierarchy for sources and sinks



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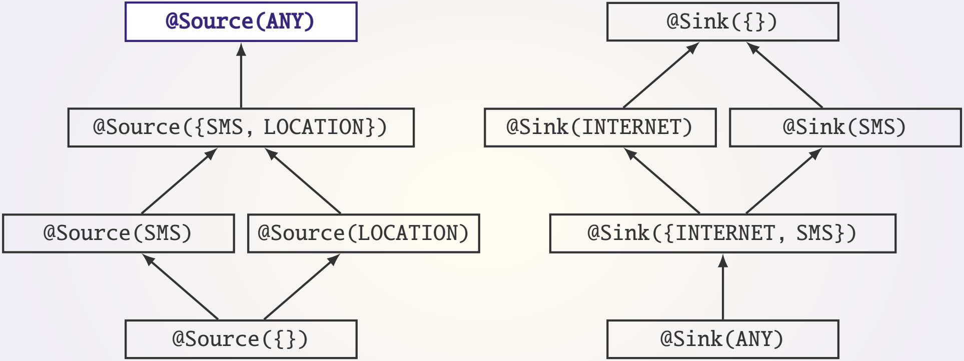
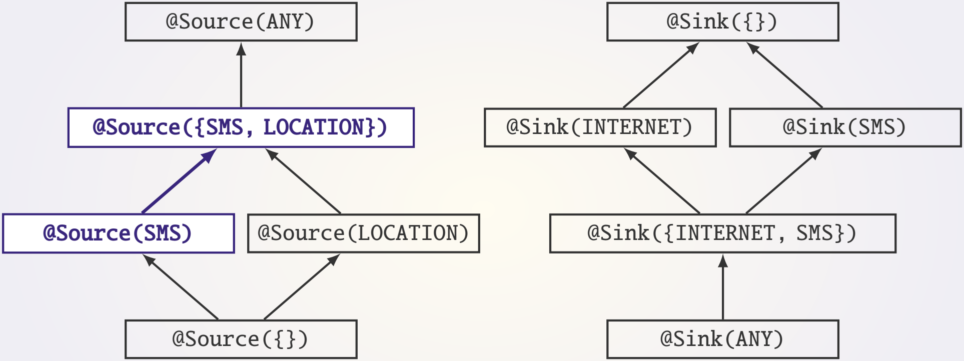



**@Source(ANY) ≡ @Source({SMS, LOCATION, INTERNET, ...})**

# Type hierarchy for sources and sinks




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

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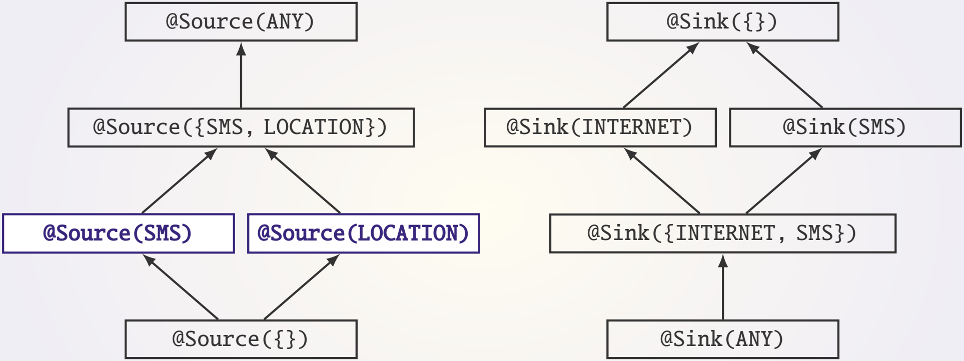


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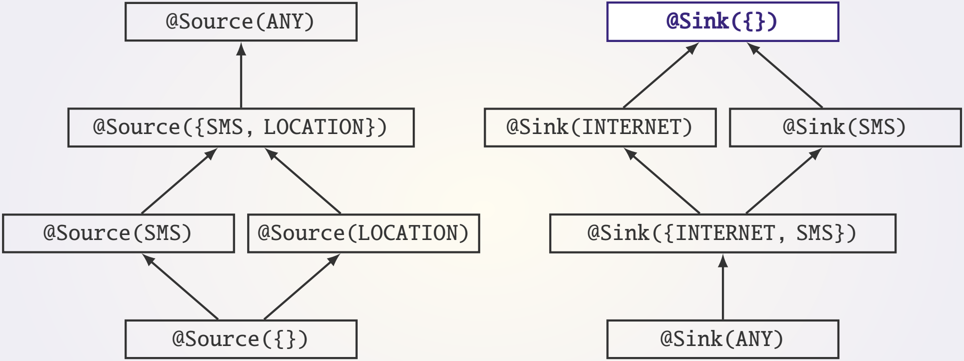

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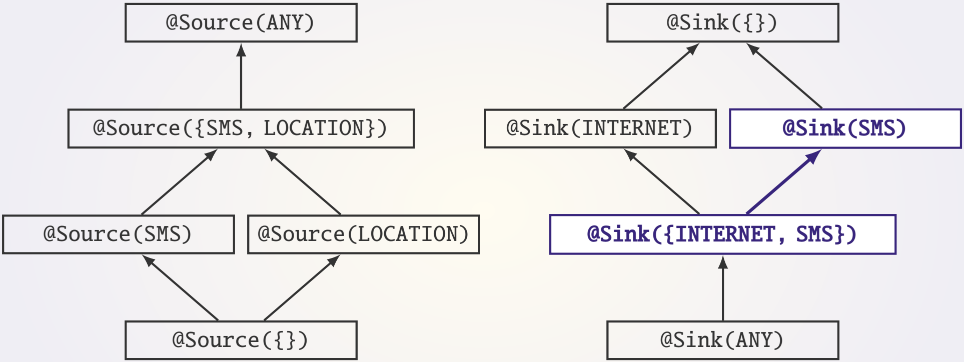


```
@Sink({INTERNET, SMS})String toInetSms;
@Sink(SMS)String toSms = toInetSms;
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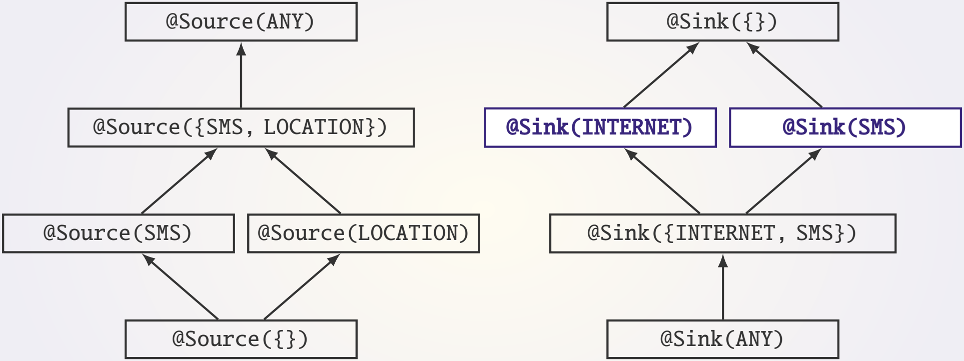


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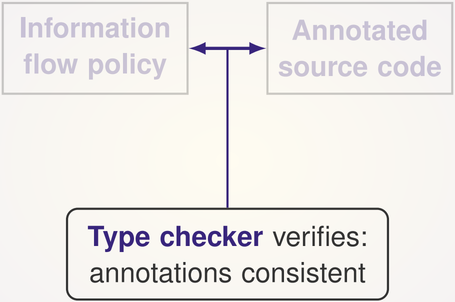

# Information Flow Type-checker (IFT): Overview

## Guarantees of type-checking

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

**Type checker** verifies:
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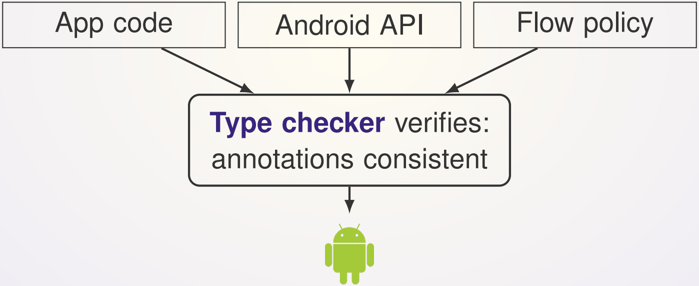


**No undisclosed information flows in app**

# 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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**Incompatible sinks:**
**INTERNET $\not<:$ SMS**

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Flow policy

```
LOCATION -> INTERNET
```

**Type checker** verifies:
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**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;
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@Source(LOCATION)

@Source(LOCATION, SMS)

# False positives and declassifications

App code

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@Source({LOCATION, SMS})String [] array;
array[0] = readGPS();
array[1] = readSMS();
@SuppressWarnings("flow") // Safe: 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

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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-checker warning for conditions with sensitive source

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**Our approach: Prune irrelevant conditions**

- Add additional sink CONDITIONAL
- Type-checker warning for conditions with sensitive source

**Analyst must manually verify**

- 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

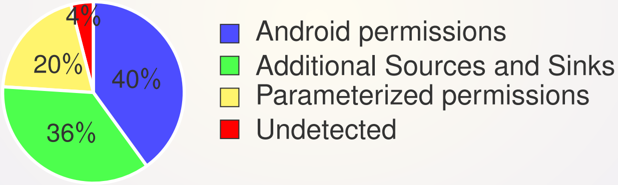
- 5 independent Red Teams
- 72 Android apps (47 malicious with information-flow malware)
- 8,000 LOC and 12 permissions per app on average

# Adversarial Red Team challenge

## Setup

- 5 independent Red Teams
- 72 Android apps (47 malicious with information-flow malware)
- 8,000 LOC and 12 permissions per app on average

## 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 per app on average

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# Usability study

## Setup

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

# Usability study

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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

## Declassifications

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

**IFT's features effectively reduce false positives**

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## 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

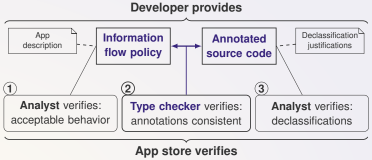
- Crowd-sourcing *(Agarwal & Hall, MobiSys'13)*
- Natural language processing *(Pandita et al., USENIX'13)*
- Clustering *(Gorla et al., ICSE'14)*

**Could aid manual verification of flow policies**

# Conclusions

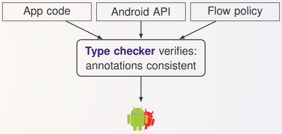
## Collaborative verification model

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



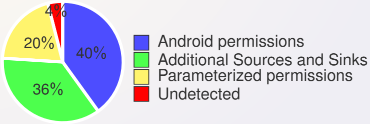

## Information Flow Type-checker (IFT)

- 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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