Software Security

Information Flow for Android Apps

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Today

1. Possibilities to make the type system of Java richer, ie. more expressive
   - using Java annotations on types

2. Using this possibility to add types for information flow
   - for Android apps

Recall from earlier lectures & lecture notes

- Typing is a great way to prevent certain classes of bugs
  - by making certain kinds of bugs *less likely*
- Type-safety (aka type-soundness) makes this even better
  - by making make certain kinds of bugs *impossible* and eliminating some weird behaviour that attackers may exploit
- Types provides the basis for more ‘safety’ guarantees, such as
  - visibility restrictions (using eg `private` fields)
  - sand-boxing (ie. code-based access control inside program)
  - immutable objects
  - keeping track of different kinds of string-like data: different languages/formats, different encodings, different trust levels

    Eg UserName vs URL vs TrustedURL vs SQLstatement vs TrustedHTML vs …

Recap: typing for information flow

Recall from last week & lecture notes (Chapter 5):

- Typing can be used to track information flows between several levels
  - using a lattice of security levels
  - for integrity or for confidentiality
- Such type systems can be overly restrictive
  - Preventing implicit flows is tricky

    ```
    if (... hi ...) { lo = ... } ; // not allowed
    ```

    (Hence s : ok t meant s only writes to level t or higher)
  - Preventing termination-leaks or timing-leaks even more so

    ```
    if (... hi ...) { ... } ; // not allowed
    ```

Java Annotations on Types

&

CHECKER
framework

Java's type system is too weak? Spot the defects

Java's type system can catch certain errors at compile-time

```
boolean b = 2.0 + "hello";
```

but not all

```
System.console().readLine();

int i = a[4];

rs = stmt.executeQuery(query);
```

possible NullPointer

possible NullPointer or IndexOutOfBounds

possible SQL injection?

Spot the defects!

Java’s type system is too weak? Spot the defect

```
int doubleLength(String s)
        {return s.length * 2; }
...
 ...
int j = doubleLength(null);
...
```

NullPointer Exception

Spot the defect!

Java’s type system does not catch this problem. A human reader can.

Whose fault is this NullpointerException?

a) the programmer who wrote the code for `doubleLength` ?

b) or: the programmer who called `doubleLength` with a `null` argument ?

Type annotations

Programmer can enrich Java’s type system with annotations of the form

```
@SomeAnnotation

@SomeAnnotationWithElements(colour = "blue", age = "18")

@SomeAnnotationWithOneElement("blue")
```

These can be added to source code

- on declarations, eg of classes, fields, methods, ...

```
public @Colour("green") class Grass {...}

protected @Colour("red") int i;

private @isCreditCardNumber int getCCN() { ... }
```

- on uses of types (since Java 8, JSR308)

```
new @Colour("green") List(...);
```

Annotation example: @NonNull and @Nullable

```
int doubleLength(@NonNull String s)
   {return s.length * 2; }
 ...
 int j = doubleLength(null); // this is ill-typed!
```

Annotation example: @NonNull and @Nullable

```
int doubleLength(@Nullable String s)
   {return s.length * 2; }    // this is ill-typed!
 ...
 int j = doubleLength(null);
```

Moral: even *without any tool* support, custom annotations can help to

- clarify assumptions & guarantees
  - and hence assign blame
- help humans to spot bugs

Tool support (by type checker) could automate this, of course.

Fancier examples

You can combine type annotations with generics, eg

```
@NonEmpty List<@NonNull String>
```

Warning: annotations on array types can be hard to read, eg

```
@NonNull String []
```

What could this mean?

a non-null array of strings

or: an array of non-nulls strings?

This is the sort of thing you have to look up with the language manual ☹

Type annotations & pluggable type systems

Why use annotations?

1. Annotations can simply be informal documentation to help the programmer

2. Annotations can be used to help static analysis tools

3. Annotations on types can be used as ‘real’ types, to improve (or *refine*) Java’s type system, if we have a type checker for them.
   - Effectively, this is a special form of 2

The CHECKER framework has been developed to make it easy to define such custom type checkers (see http://CheckerFramework.org)

Annotation example: ensuring encrypted information

```
void send(@Encrypted String msg) {...}
     // So send() expects an @Encrypted string
@Encrypted String encrypt(String s, Key k) {...}
     // So encrypt() produces an @Encrypted string
...
@Encrypted String msg1 = ...;
send(msg1); // OK?
String msg2 = ....;
send(msg2); // OK?
send(encrypt(msg2,key)); // OK?
```

Annotation example: ensuring encryption of network traffic

```
void send(@Encrypted String msg) {...}
     // So send() expects an @Encrypted string
@Encrypted String encrypt(String s, Key k) {...}
     // So encrypt() produces an @Encrypted string
...
@Encrypted String msg1 = ...;
send(msg1); // OK!
String msg2 = ....;
send(msg2); // Warning!
send(encrypt(msg2,key)); // OK!
```

Moral of the story: we can use custom annotations to help prevent certain categories of flaws

Annotation example: ensuring encryption of network traffic

The (one line!) definition of a typechecker for `@Encrypted` annotations using the Checker framework

```
@Target(ElementType.TYPE_USE)
  @SubtypeOf(Unqualified.class)
    public @interface Encrypted {}
```

SPARTA:
Static Program Analysis for Reliable Trusted Apps

Type system for information flow in Java apps

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

by

Michael D. Ernst, René Just, Suzanne Millstein, Werner Dietl, Stuart Pernsteiner, Franziska Roesner, Karl Koscher, Paulo Barros, Ravi Bhoraskar, Seungyeop Han, Paul Vines, and Edward X. Wu

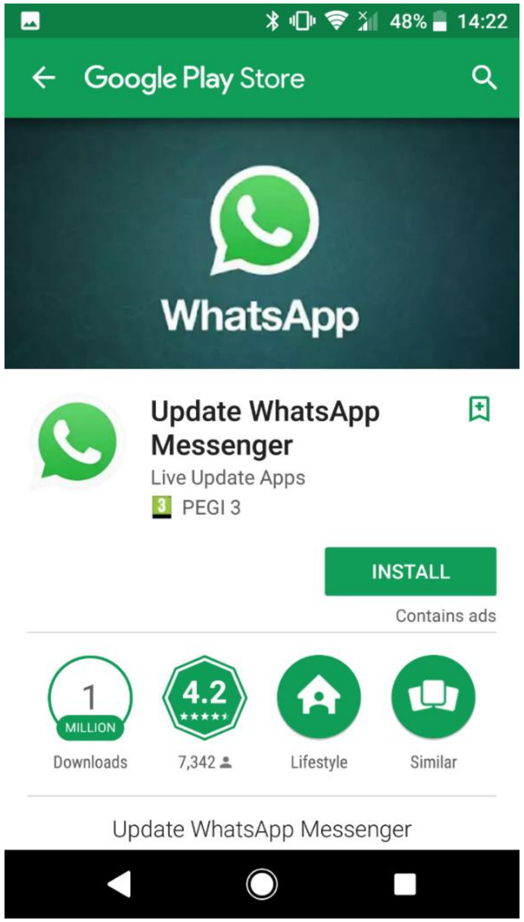
CCS 2014

This paper presents SPARTA
(Static Program Analysis for Reliable Trusted Apps)

More info at http://www.cs.washington.edu/sparta

Context: current generation of app stores

- App stores have some approval process
- They have to approve hundreds of apps per day
- Problem: all app stores have approved malware
- Current best practice: run some static analysis tool (which does not have too many false positives) and then remove malware when it is reported


Google Play Store

Update WhatsApp Messenger

Live Update Apps

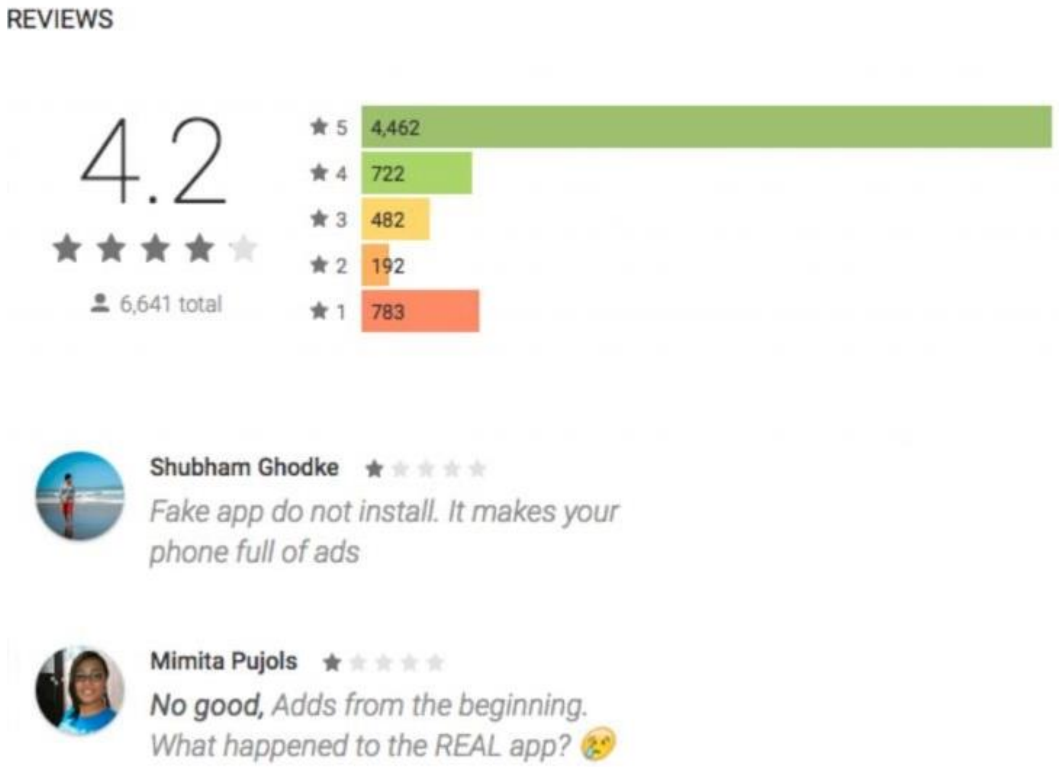
PEGI 3

INSTALL

Contains ads

1 MILLION	4.2		
Downloads	7,342	Lifestyle	Similar

Update WhatsApp Messenger


REVIEWS

4.2

6,641 total

5	4,462
4	722
3	482
2	192
1	783

Shubham Ghodke

Fake app do not install. It makes your phone full of ads

Mimita Pujols

No good, Adds from the beginning. What happened to the REAL app? 😢

Fake WhatsApp app in Google Playstore in Nov. 2017, with > 1 million installs

Security worries in apps

Malware can

1. steal user information (location, installed apps, ..)
2. steal user credentials (passwords, ...)
3. make premium calls or send expensive SMS
4. send SMS advertising
5. improve website rankings in search engine results
   - this is a form of SEO (Search Engine Optimisation) that search engines disapprove of
6. do some purposeless destruction
7. ransomware

SPARTA can prevent 1-4

- but not phishing as way to steal credentials, which is also a form of 2

Better app stores offering higher assurance level

- Could a specialised app store provide higher level of assurance?

  Eg for special categories of apps or users, such as

  - financial or medical apps,
  - corporate or government users

- Could there be a business model in this?

  To make extra effort commercially viable or even profitable.

- *Bottlenecks:*

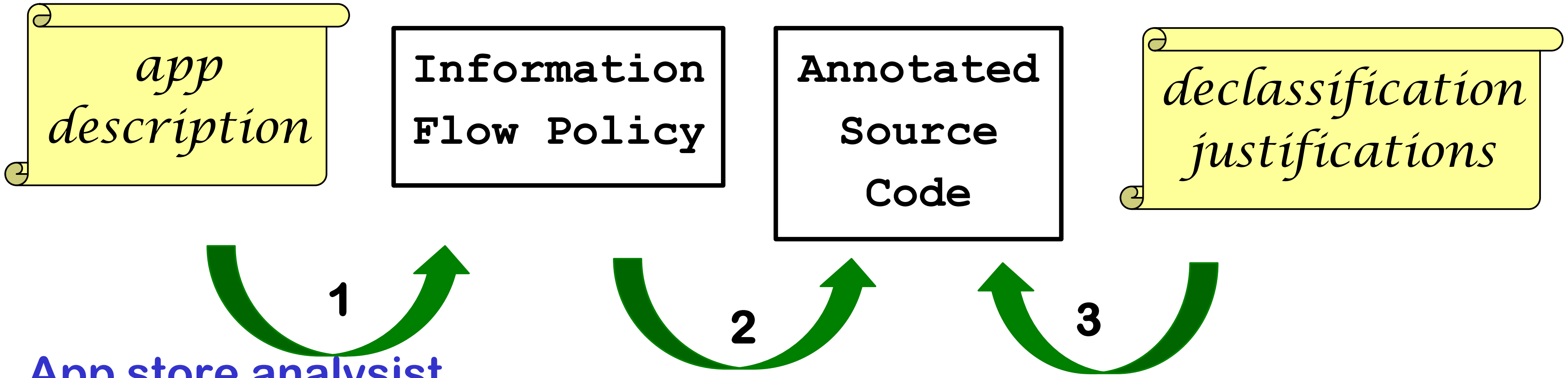
  1. *what to check ?*
  2. *how to check?*
  3. *can this be done at reasonable cost (time & effort)?*

SPARTA

- Security type system for Android apps
  - to guarantee information flow policies,
    that rule out unwanted information leaks
- Java annotations used to annotate code
- Checker framework is used to type check these
  - *but* some manual checks for declassification,
    incl. manual checks for implicit flows in conditional statements
- Collaborative verification, where
  1. code developer does some work by adding annotations
  2. human verifier runs checker & performs manual checks

Collaborative verification model

- Developer provides



- App store analysist

1. checks if information flow policy is acceptable (manually)
2. runs the type checker
3. checks the declassifications (manually)

What to check? Information flow policies!

The target: preventing malware with unwanted information flows

Information flow policies specified using sources and sinks, where information comes from or goes to

Example sources

- camera
- location information
- SMS reading
- the file system

Example sinks

- the display
- the internet
- SMS sending
- the file system

- Many sources and sinks already occur as Android permissions
- Some things can be both source and sink, eg. the file system

Android permissions vs information flow policies

- An app can have Android permission to access
  - location information
  - internet connection
  - camera
  - file system
- As an information flow policy, the app could *only* have permission to
  - save camera image to disk (ie not to send it over the internet)
  - save location to disk (eg, to save location with a photo)
  - download updates over the internet connection

This is much more fine-grained! But maybe still not perfect…

As discussed last week, information flow policies are more expressive than conventional access control policies.

Example information flow policies

```
READ_SMS     -> DISPLAY

USER_INPUT   -> CALL_PHONE

CAMERA       -> DISPLAY, DATA

LOCATION     -> INTERNET(maps.google.nl)
```

Sources and sinks may be parameterised.

Notation: `->` is also written as `!` in the paper

Transitivity?

Does the policy

```
CAMERA       -> FILESYSTEM

FILESYSTEM   -> INTERNET
```

also allow

```
CAMERA       -> INTERNET    ?
```

Transitivity & white-washing

Transitive flows must be explicitly specified.

So the policy

```
        CAMERA       -> FILESYSTEM
        FILESYSTEM   -> INTERNET
```

must also include

```
        CAMERA       -> INTERNET
```

if photes are allowed to be sent over the internet.

Idea: make sure an app cannot whitewash data via file system if this was not explicitly intended.

Parameters could also rule out such issues, eg

```
                CAMERA          -> FILESYSTEM("images/*")
    FILESYSTEM("config/*")      -> INTERNET
```

Information flow types: sources and sinks

`@Source` Where might this info come from?

`@Sink` Where might this info go to?

These type annotations take a parameter (or *element*, in Java terminology) and are then applied to variables or parameters.

For example

`@Source(CAMERA)` – this info comes, or *might* come, from the camera

`@Source(LOCATION)` – this info may be location information

`@Sink(INTERNET)` – this info may be sent over the internet

`@Source(INTERNET,CAMERA)` – this info may come from camera or internet

Example type annotations

Suppose the Android API includes methods

```
    public static void sendToInternet(String s);

    public static String readGPS();
```

What would be good annotations of these methods ?

```
    public static void sendToInternet(@Sink(INTERNET) s);

    public static @Source(LOCATION)String readGPS();
```

Example typings

Given the API methods

```
void sendToInternet(@Sink(INTERNET) String message);

@Source(LOCATION)String readGPS();
```

What would be a correct annotation of the app code below?

```
String loc = readGPS();

sendToInternet(loc);
```

Example typings

API annotations are given and trusted

Given the API methods

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

What would be a correct annotation of the app code below?

```
@Source(LOCATION)@Sink(INTERNET) String loc = readGPS();
// loc may receive LOCATION info
//     and may be sent over internet
sendToInternet(loc);
```

app annotations are to be provided by app developer and are not trusted

This code is only acceptable if the policy includes `LOCATION->INTERNET`

Example typings

Which of these annotations would be rejected by the type checker?

1. `@Source(LOCATION) String loc = readGPS();`
   `sendToInternet(loc);` ✗

   - Not type correct, because in 2nd line `loc` cannot be sent over internet

2. `@Sink(INTERNET) String loc = readGPS();` ✗
   `sendToInternet(loc);`

   - Not type correct, because in 1st line `loc` can't store location information

3. `String loc = readGPS();` ✗
   `sendToInternet(loc);` ✗

   - Not type correct, because of same reasons as 1 and 2

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

   - Type correct, but does require policy includes `LOCATION->INTERNET`

Moral of the story: programmers have to get annotations right to make their code typecheck, and cannot cheat!

Is this code ok?

```
@Source(SMS) String s = ... ;

@Source(SMS,INTERNET) String t = s;
```

Yes, as `@Source(SMS)` is a subset of `@Source(SMS,INTERNET)`

```
@Source(SMS) @Sink(SMS,INTERNET) String msg1 = ...;

@Source(SMS,INTERNET) @Sink(SMS) String msg2 = msg1;
```

Yes, as `@Sink(SMS)` is a subset of `@Sink(SMS,INTERNET)`

Beware: with aliasing between mutable data structures you have to be careful!

Eg having two references to the same `char[]` with different annotations, say `@Sink(SMS,INTERNET)` and `@Sink(SMS)`, would cause unsoundness

Subtyping

There is a natural subtyping relation on types.

For example,

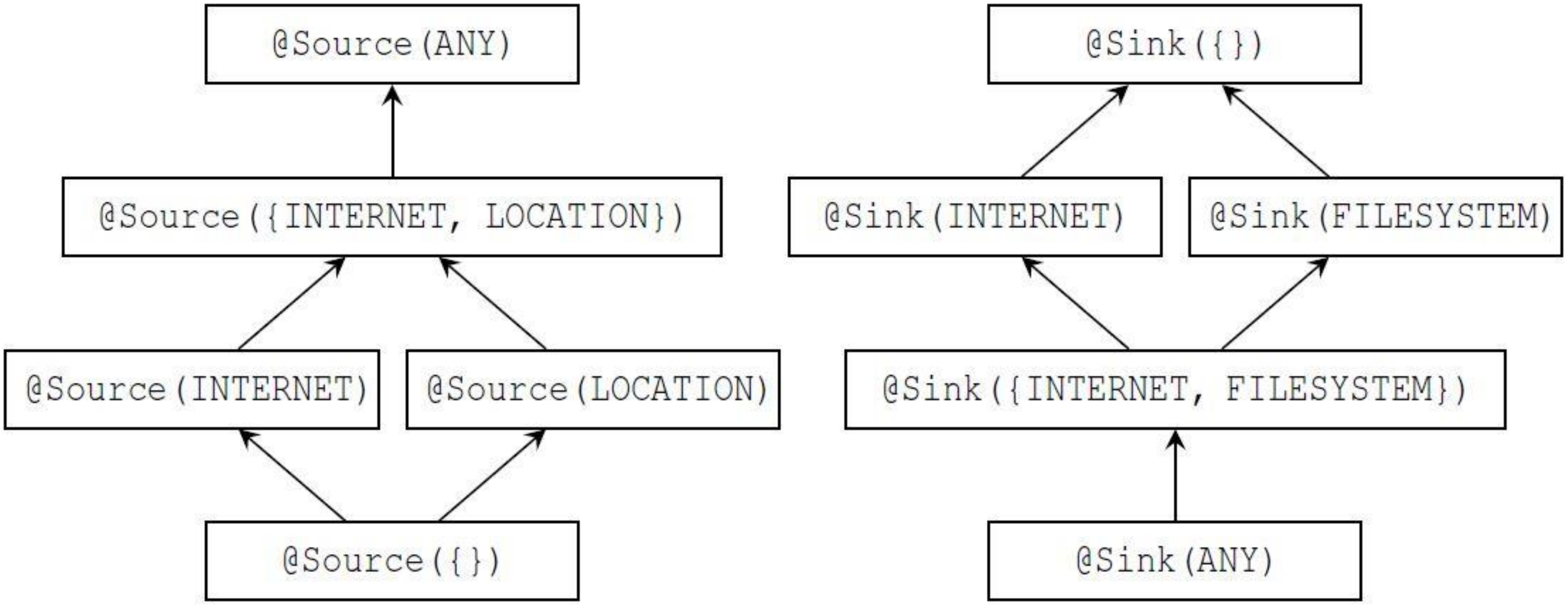
`@Source(SMS)` is a subtype of `@Source(SMS,INTERNET)`

`@Sink(SMS,INTERNET)` is a subtype of `@Sink(SMS)`

Note the opposite direction of the subtype relation for Sources and Sinks.

- Recall: we also saw this duality in type systems for information flow
  for reading information of some level
  vs writing information to a variable of some level

The subtype relation forms a lattice



```
@Source(ANY) = @Source{LOCATION, INTERNET, SMS, CAMERA, ...}
```

Subtyping

The subtype relation gives rise to a subtyping rule in the type system.

- Eg, if

  ```
  @Source(SMS) String s;
  ```

  then `s` also has type `@Source(SMS,INTERNET)`

Recall subtyping rule (aka subsumption) from last week & lecture notes

$$\frac{e : t \qquad t \leq t'}{e : t'}$$

Quiz: is this app code ok & does it meet policy?

App code:

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

sendToInternet(loc);
```

Policy:

```
LOCATION -> INTERNET
```

✓

Quiz: is this app code ok & does it meet policy?

App code:

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

Policy:

```
LOCATION -> SMS
```
✗

```
LOCATION -> SMS,INTERNET
```
✓

Quiz: is this app code ok & does it meet policy?

App code:

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

sendToInternet(loc);
```

Policy:

```
LOCATION -> SMS
```

✗

Quiz: is this app code ok & does it meet policy?

App code:

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

Policy:

```
LOCATION -> INTERNET
```
✗

The code does meet the policy, but the app developer screwed up the annotations, so the type checker will complain!

The tricky cases...

Problematic cases

- The SPARTA type system is overly restrictive

  Some ‘legal’ programs (which do not violate the policy) will be rejected

  - ie. there are false positives

- Solution to this:
  - The type system provides explicit loopholes for this
  - Any use of these loopholes will have to be manually verified

Problem 1: heterogeneous arrays

```
String[] a;

a[0] = readGPS();

a[1] = readSMS();
```

What would be a good annotation of the code above, using the parameter ***`LOCATION`*** *and* ***`SMS`****?*

Problem 1: heterogeneous arrays

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

a[0] = readGPS();

a[1] = readSMS();
```

What would be a good annotation of the code above, using the parameter `LOCATION` and `SMS`?

This is not the most accurate description, we 'lose' some information, namely that the two array elements have different types.

The annotation system is not expressive enough to talk about such heterogenous arrays.

Problem 1: heterogeneous arrays

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

a[0] = readGPS();

a[1] = readSMS();

String loc = a[0];
```

What would be a good annotation of the code above?

Problem 1: heterogeneous arrays

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

a[0] = readGPS();

a[1] = readSMS();

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

We would like to be more precise and write

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

but then the type checker will complain, even though this complaint is a false positive

- *as this declassification is ok*

Problem 1: heterogeneous arrays

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

a[0] = readGPS();

a[1] = readSMS();

@SuppressWarnings("flow") // Always returns location data

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

App developer can use this to surpress false positives.

But the human verifier will have to manually verify these!

Problem 2: Dealing with implicit flows

```
@Source(USER_INPUT) long pin = getPINCode();

long i=0;

while (true) { if (i == pin) { sendToInternet(i); }

                 i++;

               }
```

Possible approaches

1. Ignoring implicit flows: this would be unsound, and allow leaking of the PIN code

2. Classic, sound approach, as in lecture notes:
   inside an if-statement we can only send stuff over the internet
   if all variables used in the guard can be sent over the internet.
   This becomes *very* restrictive!

3. Solution used in SPARTA: introduce a new sink `CONDITIONAL`

Problem 2: Dealing with implicit flows

```
@Source(USER_INPUT) long pin = getPINCode();

long i=0;

while (true) { if (i == pin) { sendToInternet(i); }

               i++;

             }
```

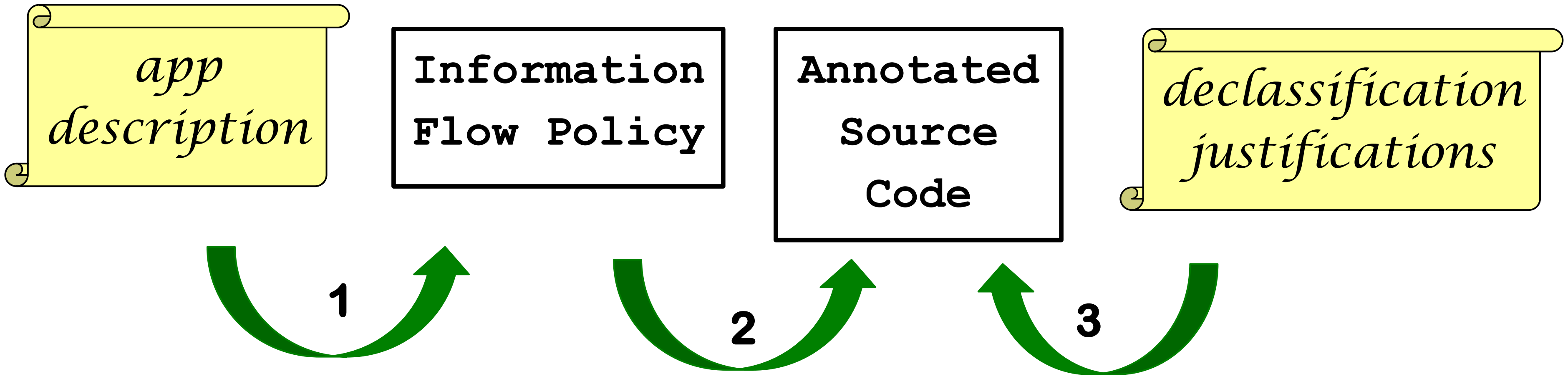
```
USER_INPUT -> CONDITIONAL
```

SPARTA’s approach to implicit flows

- New sink `CONDITIONAL`
- Flows to `CONDITIONAL` if classified information is used in a condition
- Type checker will warn about these
- Human verifier will have to check these

Overview: SPARTA's collaborative verification model

- Developer provides



- App store analysist
  1. checks if information flow policy is acceptable
  2. runs the type checker
  3. manually checks the declassifications

Trusted Computing Base (TCB)

What is in the Trusted Computing Base? And what not?

1. The Android OS, incl the Java Virtual Machine
2. The type checker for annotations
3. The Java compiler & byte code verifier
4. The annotations provided for the APIs
5. The annotations provided by the app developer
6. The human verifier

Trusted Computing Base (TCB)

What is in the Trusted Computing Base? And what not?

1.	The Android OS, incl the Java Virtual Machine	YES
2.	The type checker for annotations	YES
3.	The Java compiler & byte code verifier	YES
4.	The annotations provided for the APIs	YES
5.	*the annotations provided by the app developer*	*NO*
6.	The human verifier	YES

Tricky case: generics

- Java annotations interact with generics in the obvious way, eg

```
List <@Source(USER_INPUT) @Sink(SMS) String> myList;
```

though reading these can get tricky…

Problem 3: generics & polymorphic functions

How to annotate a function such as

```
static char[] stringToCharArray(String s) ?
```

This function is polymorphic: it preserves any type annotation on the input.

So

1. if `x` is `@Sink(SMS)` then `stringToCharArray(x)` is `@Sink(SMS)`
2. if `x` is `@Sink(INTERNET)` then `stringToCharArray(x)` is `@Sink(INTERNET)`

But we cannot a single annotation that covers both 1 and 2…

Solution: in annotations we can quantify over all type annotations, using a special type annotation variable `@PolySource`

```
@PolySource char[] stringToCharArray(@PolySource String s)
```

Recall we had the same problem with tainting annotation for `array_copy` with PREfast

Case study with SPARTA (see paper)

- Analysis of 72 apps written by Red Team
- (Relatively low) annotation burden: 6 annotations/100 loc
- Auditing (ie human verifier) burden: 30 minutes/ kloc
  - but is this acceptable for several Mbytes of code?
- 96% of information flow related malware found
  (It's hard to find in the paper what the problem with the remaining 4% is, but it is claimed that extensions discussed in 2.10 would fix them)
- This was 82% of all malware in these apps, as some malware behaviour was not about unwanted information flow

To read

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CCS 2014

See link on course webpage.

Types for security: this week vs few weeks ago

SPARTA

Eg `@Source(LOCATION)`

`@Sink(SMS)`

- Types (type annotations) for ***confidentiality*** in Java

- *Could we use a SPARTA-like approach for integrity too?*

  YES!

- Implicit flows are a clear problem for confidentiality

Google's Trusted Types

aka API hardening

Eg `SafeScript` `SafeUrl`

`TrustedResourceUrl` `SafeHtml`

- Types for ***integrity*** aka tainting in JavaScript

- Not so clear if implicit flows are a problem for integrity