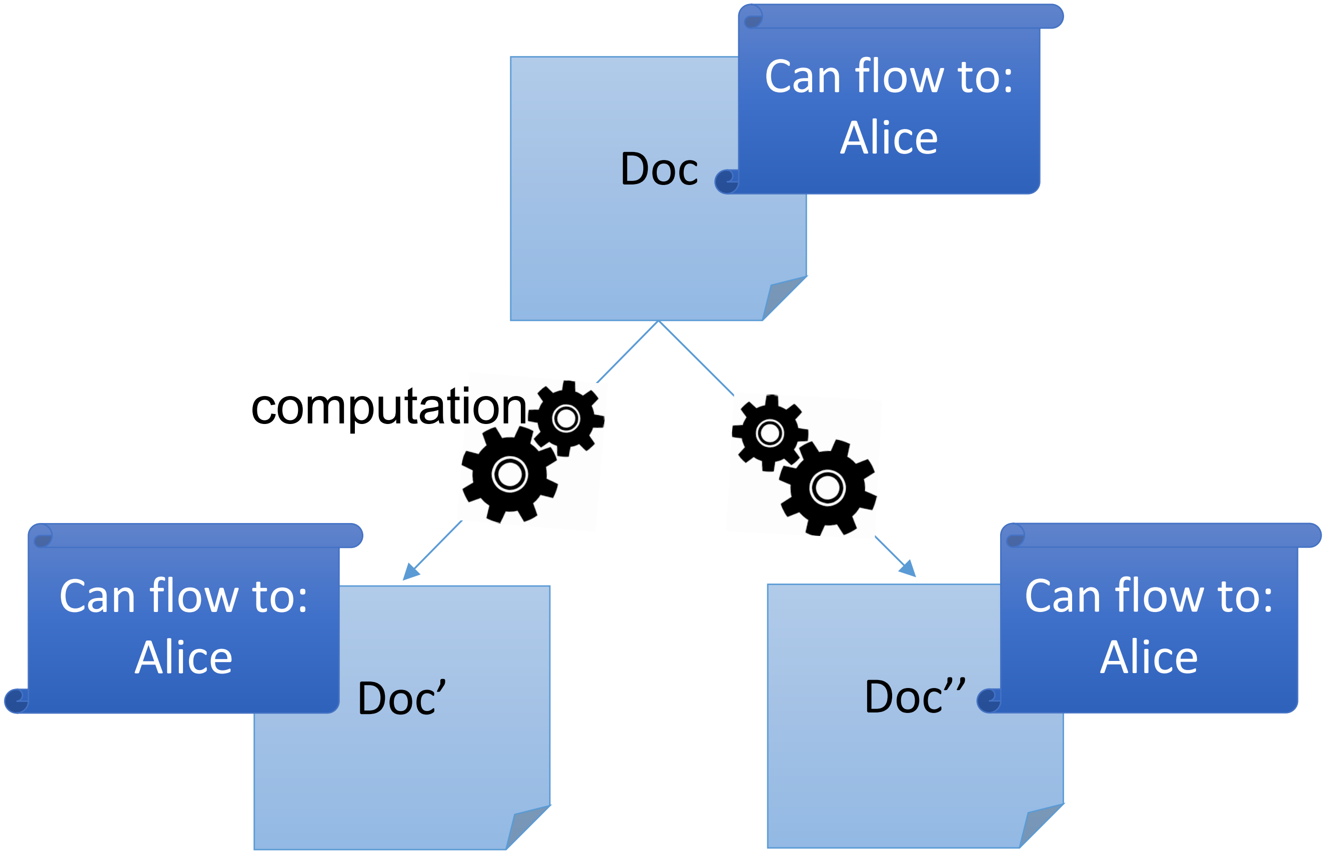
Lecture 21: Dynamic Information Flow Control

CS 5430

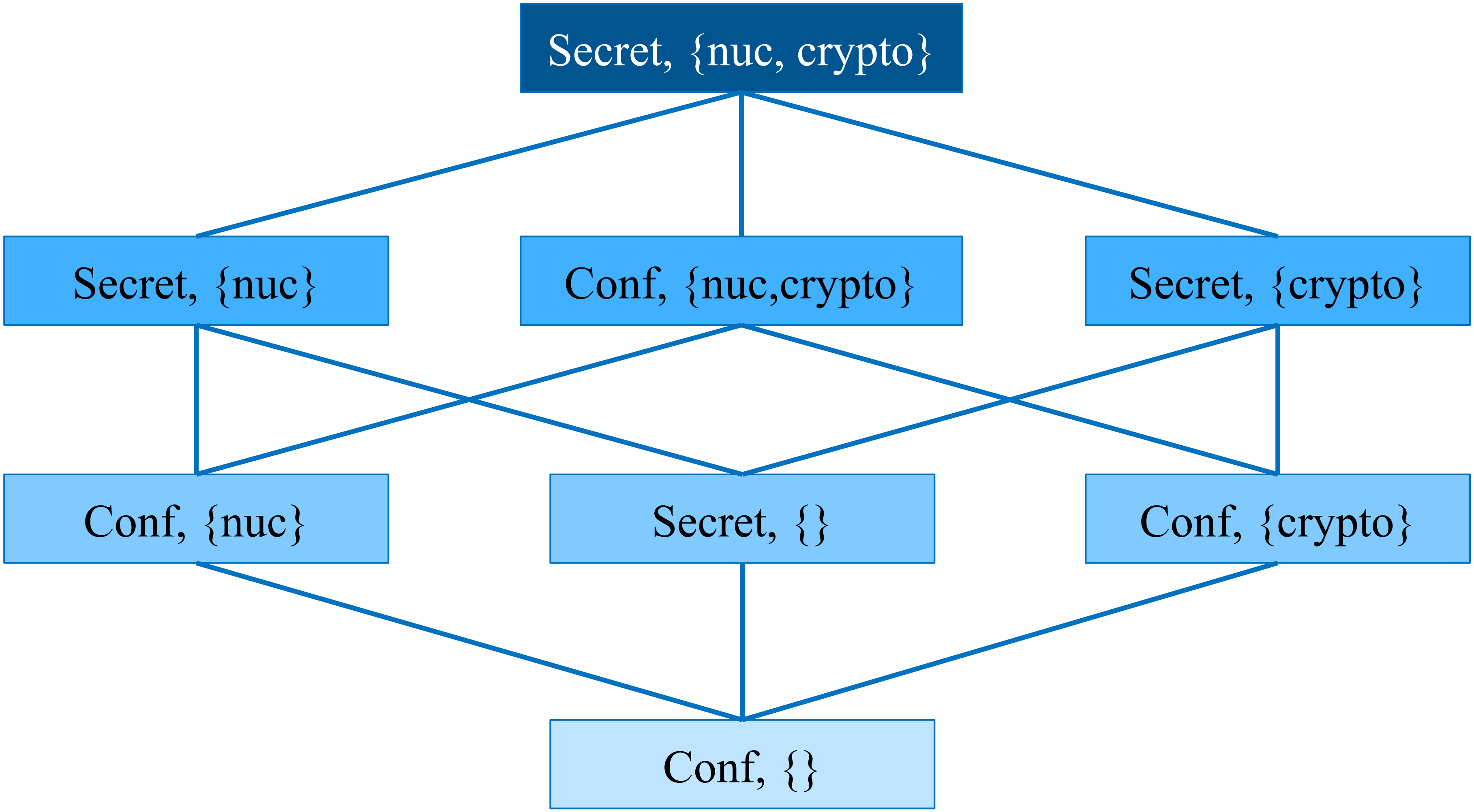
4/16/2018

Information flow policies



Automatic deduction of policies!

Labels represent policies



Secret, {nuc, crypto}

Secret, {nuc}

Conf, {nuc,crypto}

Secret, {crypto}

Conf, {nuc}

Secret, {}

Conf, {crypto}

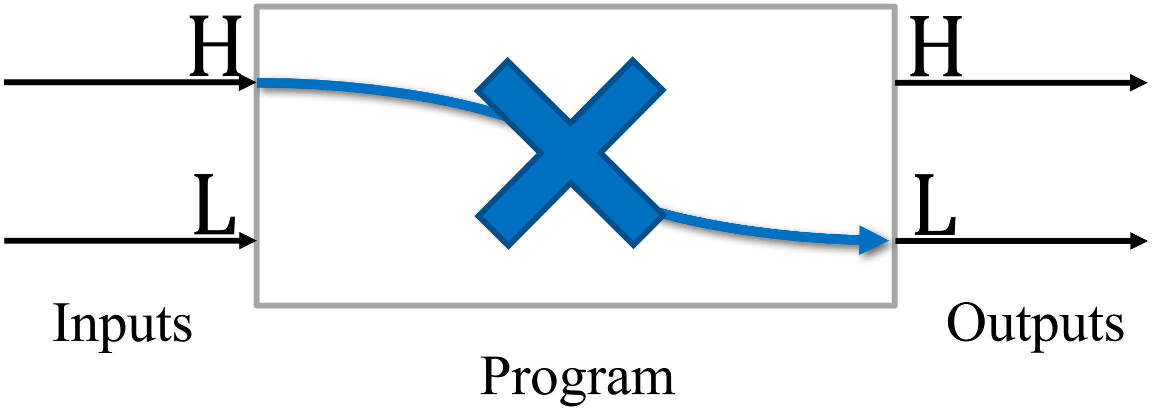
Conf, {}

Noninterference

[Goguen and Meseguer 1982]

An interpretation of noninterference for a program:

- Changes on H inputs should not cause changes on L outputs.



Static type system

Assignment-Rule:
$$\frac{\Gamma \vdash \mathbf{e} : \ell \qquad \ell \sqcup ctx \sqsubseteq \Gamma(\mathbf{x})}{\Gamma\,,\, ctx \vdash \mathbf{x{:=}e}}$$

If-Rule:
$$\frac{\Gamma \vdash \mathbf{e} : \ell \qquad \Gamma\,,\, \ell \sqcup ctx \vdash \mathbf{c1} \qquad \Gamma\,,\, \ell \sqcup ctx \vdash \mathbf{c2}}{\Gamma\,,\, ctx \vdash \mathbf{if\ e\ then\ c1\ else\ c2}}$$

While-Rule:
$$\frac{\Gamma \vdash \mathbf{e} : \ell \qquad \Gamma\,,\, \ell \sqcup ctx \vdash \mathbf{c}}{\Gamma\,,\, ctx \vdash \mathbf{while\ e\ do\ c}}$$

Sequence-Rule:
$$\frac{\Gamma\,,\, ctx \vdash \mathbf{c1} \qquad \Gamma\,,\, ctx \vdash \mathbf{c2}}{\Gamma\,,\, ctx \vdash \mathbf{c1;c2}}$$

This type system is not complete.

- `c` satisfies noninterference $\not\Rightarrow$ $\Gamma, ctx \vdash$ `c`
    - There is a command `c`, such that noninterference is satisfied, but `c` is not type correct.
- Example 1:
    - $\Gamma(\mathbf{x}) = \mathrm{H}, \Gamma(\mathbf{y}) = \mathrm{L}$
    - `c` is `if x>0 then y:=1 else y:=1`
- Example 2:
    - $\Gamma(\mathrm{x}) = \mathrm{H}, \Gamma(\mathrm{y}) = \mathrm{L}$
    - `c` is `if 1=1 then y:=1 else y:=x`
- So, this type system is *conservative*. It has *false negatives:*
    - There are programs that are not type correct, but that satisfy noninterference.

Can we build a complete mechanism?

- Is there an enforcement mechanism for information flow control that has no false negatives?
  - A mechanism that rejects only programs that do not satisfy noninterference?
- No! [Sabelfeld and Myers, 2003]
  - "The general problem of confidentiality for programs is undecidable."
  - The halting problem can be reduced to the information flow control problem.
  - Example:

```
if h>1 then c; l:=2 else skip
```

    - If we could precisely decide whether this program is secure, we could decide whether `c` terminates!

DYNAMIC ENFORCEMENT

Dynamic Enforcement

- Dynamic mechanisms use run time information to decrease false negatives.
- A dynamic mechanism (monitor) checks/deduces labels along the execution:
  - When an assignment **`x:=e`** is executed,
    - either check whether $\Gamma(\mathbf{e}) \sqcup ctx \sqsubseteq \Gamma(\mathbf{x})$ holds (fixed Γ),
      - The execution of a program is halted when a check fails.
    - or deduce $\Gamma(\mathbf{x})$ such that $\Gamma(\mathbf{e}) \sqcup ctx \sqsubseteq \Gamma(\mathbf{x})$ holds (flow-sensitive Γ).
  - Monitor maintains a context label ctx. When execution enters a conditional command, the mechanism augments ctx with the label of the guard.

Dynamic Enforcement

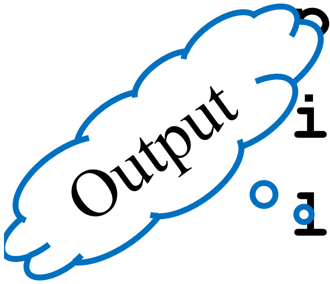
- Example 2:
  - $\Gamma(\mathrm{x}) = \mathrm{H}, \Gamma(\mathrm{y}) = \mathrm{L}$
  - **`c`** is **`if 1=1 then y:=1 else y:=x`**
  - **`c`** satisfies noninterference, because **`x`** does not leak to **`y`**.
  - dynamic check $\Gamma(\mathtt{1}) \sqcup \Gamma(\mathtt{1{=}1}) \sqsubseteq \Gamma(\mathtt{y})$ always succeeds, because branch **`y:=x`** is never taken.
  - Remember: the static type system rejects this program before execution, even though the program is secure!

But, there is a caveat…

- A dynamic mechanism may leak information
  - when deciding to halt an execution due to a failed check (fixed Γ), or
  - when deducing labels during execution (flow-sensitive Γ).

Leaking through halting (fixed Γ)

- Consider fixed Γ: Γ(**`h`**)=L and Γ(**`l`**)=H.
- Consider program:



```
p:=0;
if h>0 then l:=1 else h:=1;
l:=2
```

- If **`h>0`** is *true*, then execution is halted.
  - No public output.
- If **`h>0`** is *false*, then execution terminates normally.
  - One public output.
- Problem: **`h>0`** is leaked to public outputs.

But, there is a caveat…

- A dynamic mechanism may leak information
  - when deciding to halt an execution due to a failed check (fixed Γ), or
  - when deducing labels during execution (flow-sensitive Γ).

Leaking through labels (flow-sensitive Γ)

- Initially: $\Gamma(\mathbf{x}) = \mathrm{L}$, $\Gamma(\mathbf{y}) = \mathrm{L}$, $\Gamma(\mathbf{h}) = \mathrm{H}$

```
x:=0;
if h>0 then x:=1 else skip
y:=x
```

Output

- At termination, when $\mathbf{h} \not> \mathbf{0}$: $\Gamma(\mathbf{y}) = \Gamma(\mathbf{x}) = \mathrm{L}$.
  - Two public outputs.
- At termination, when **h>0**: $\Gamma(\mathbf{y}) = \Gamma(\mathbf{x}) = \mathrm{H}$.
  - No public output.
- Problem: Even though **h** flows to **x**, **x** is tagged with H only when **h>0**. So, **h>0** is leaked to public outputs.

The Problem with Dynamic Mechanisms

- Purely dynamic mechanisms are usually unsound.
- Purely dynamic mechanism with additional restrictions can become sound:
  - Restriction: Stop execution whenever the guard expression of a conditional command is high.
  - But, the resulting mechanism is more conservative than desired.
- Alternatively…

Use on-the-fly static analysis

- Use on-the-fly static analysis to update the labels of target variables in untaken branch.
- The resulting mechanism is sound and less conservative.

Use on-the-fly static analysis

Problem: **`x`** was tagged with H only when **`h>0`** was true, even though **`h`** always flow to **`x`**.
Goal: **`x`** should be tagged with H at every execution.

```
x:=0;
if h>0 then x:=1 else skip
```

`h>0` is evaluated to *false*.

Execute taken branch.

Use on-the-fly static analysis

Problem: **`x`** was tagged with H only when **`h>0`** was true, even though **`h`** always flow to **`x`**.
Goal: **`x`** should be tagged with H at every execution.

```
x:=0;
if h>0 then x:=1 else skip
```

On-the-fly static analysis:
$\Gamma(\mathbf{x}) = \Gamma(\mathbf{1}) \sqcup \Gamma(\mathbf{h>0}) = \mathrm{H}$

Apply on-the-fly static analysis to the untaken branch.

Use on-the-fly static analysis

Problem: **`x`** was tagged with H only when **`h>0`** was true, even though **`h`** always flow to **`x`**.

Goal: **`x`** should be tagged with H at every execution.

```
x:=0;
if h>0 then x:=1 else skip
```

$\Gamma(\mathbf{x}) = \mathrm{H}$

Static versus Dynamic

- Static:
  - Low run time overhead.
  - No new covert channels.
  - More conservative.
- Dynamic
  - Increased run time overhead.
  - Possible new covert channels.
  - Less conservative.
- Ongoing research for both static and dynamic.
  - Different expressiveness of policies, different NI versions, different mechanisms.

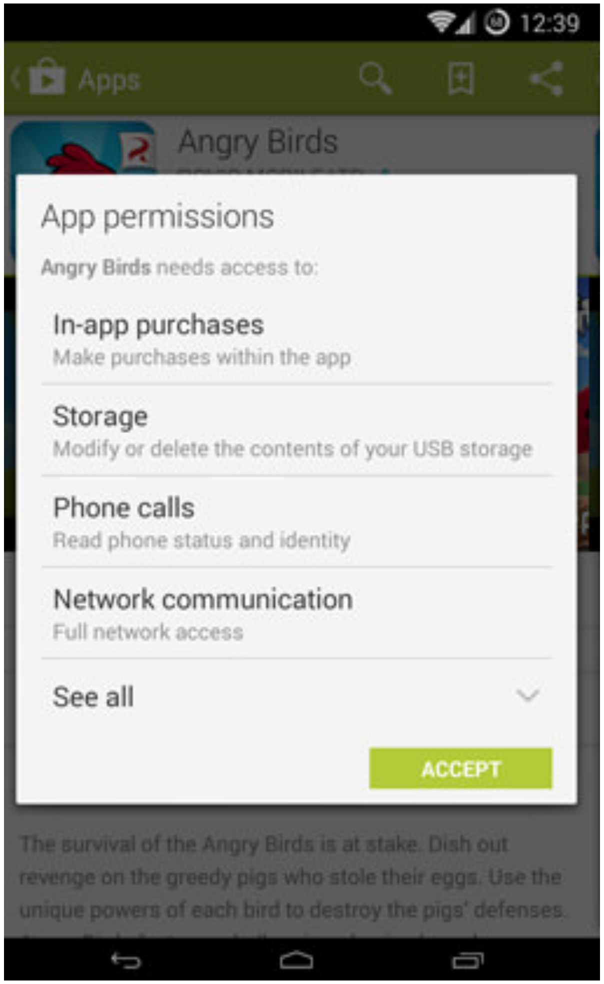
INFORMATION FLOW CONTROL IN PRACTICE(ISH)

Past and current research on dynamic analysis

- RIFLE (ISA) [Vachharajani et al. 2004]
- HiStar (OS) [Zeldovich et al. 2006]
- Trishul (JVM) [Nair et al. 2008]
- TaintDroid (Android) [Enck et al. 2010]
- LIO (Haskell) [Stefan et al. 2011]
- ...

TaintDroid

- Smartphones run apps developed by (potentially untrusted) third parties
- Apps can access sensitive information (location, contacts, etc.)
- In Android, users grant apps particular permissions on download
- End-user license agreement (EULA) states how information will be used
- How can you tell whether app behavior follows its permissions?



App permissions

Angry Birds needs access to:

In-app purchases
Make purchases within the app

Storage
Modify or delete the contents of your USB storage

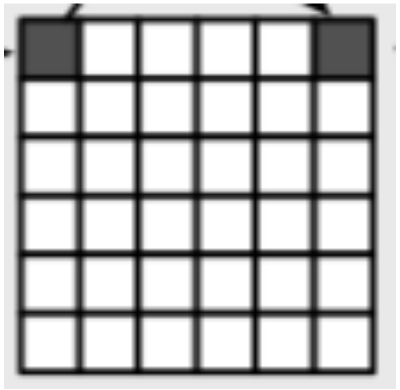
Phone calls
Read phone status and identity

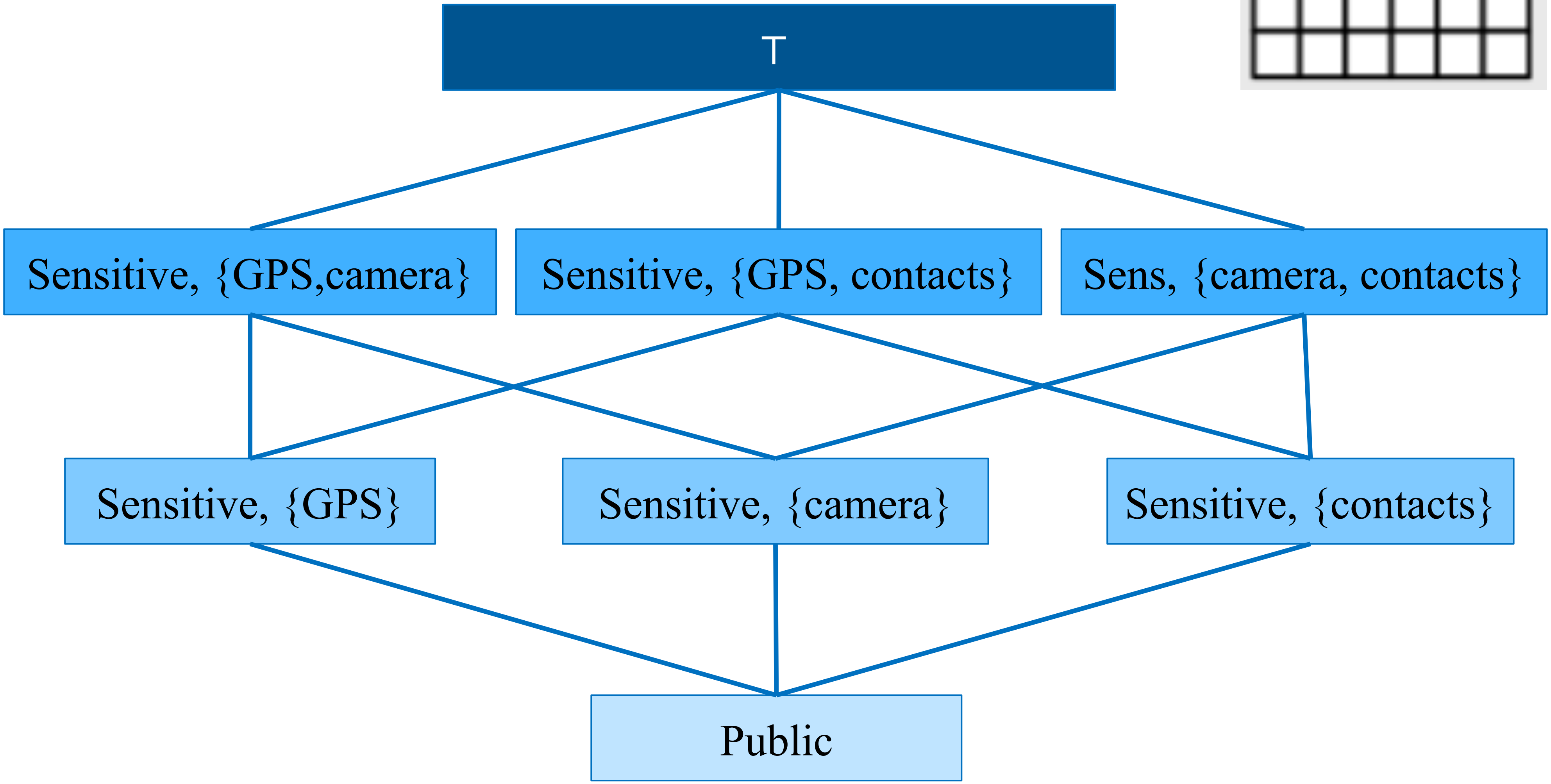
Network communication
Full network access

See all

The survival of the Angry Birds is at stake. Dish out revenge on the greedy pigs who stole their eggs. Use the unique powers of each bird to destroy the pigs' defenses.

TaintDroid Labels





T

Sensitive, {GPS,camera}

Sensitive, {GPS, contacts}

Sens, {camera, contacts}

Sensitive, {GPS}

Sensitive, {camera}

Sensitive, {contacts}

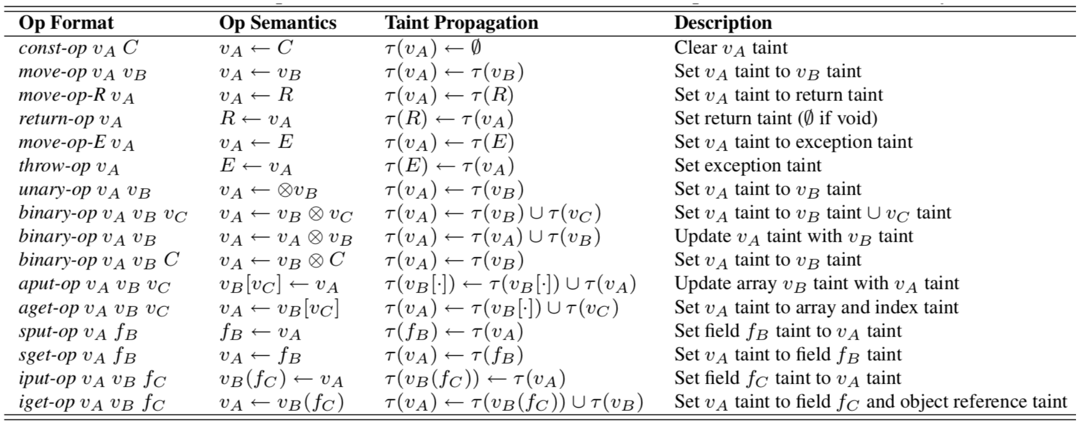
Public

Android Background Info

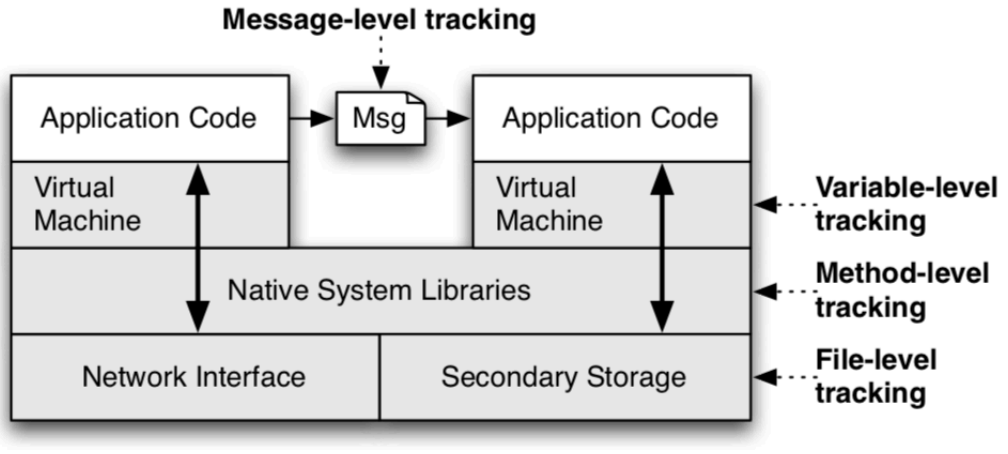
- Linux-based, open source, mobile-phone platform
- Middleware written in Java and C/C++.
- Functionality implemented by (3rd party) applications.
- Apps run on top of middleware.
- Applications written in Java.
- Compiled into Dalvik Executable(DEX) byte-code format.
  - custom byte-code
  - Register-based as opposed to stack-based.
- Executes within Dalvik VM interpreter instance.
  - Runs isolated on the platform.
  - Has unique UNIX user ids.
  - Communicate via binder IPC mechanism.

TaintTracking

- Instrument VM interpreter to provide variable-level taint tracking
- Use message-level tracking between apps
- Use method-level tracking in native libraries
- Use file-level tracking for persistent data



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 field f_C and object reference taint

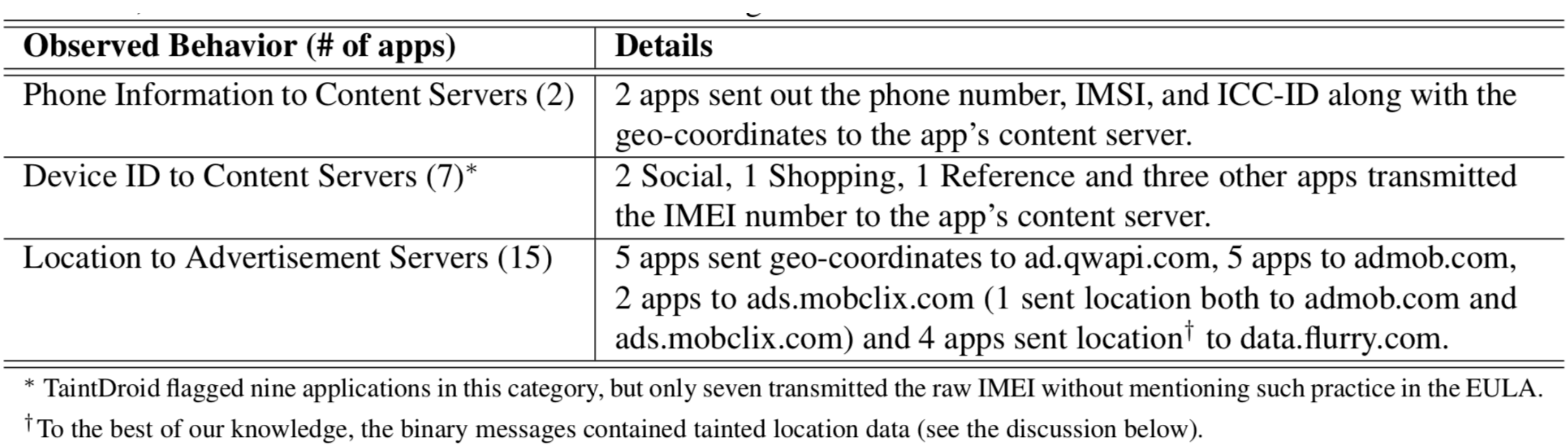


Limitations

- Dynamic IFC mechanisms incur run-time overhead
  - 14% for CPU bound microbenchmark
  - Negligible for interactive applications
- Doesn't capture implicit flows

Experimental Findings

- Researchers studied real-world apps with TaintDroid
- Of 30 apps, found:



Observed Behavior (# of apps)	**Details**
Phone Information to Content Servers (2)	2 apps sent out the phone number, IMSI, and ICC-ID along with the geo-coordinates to the app's content server.
Device ID to Content Servers (7)*	2 Social, 1 Shopping, 1 Reference and three other apps transmitted the IMEI number to the app's content server.
Location to Advertisement Servers (15)	5 apps sent geo-coordinates to ad.qwapi.com, 5 apps to admob.com, 2 apps to ads.mobclix.com (1 sent location both to admob.com and ads.mobclix.com) and 4 apps sent location† to data.flurry.com.

* TaintDroid flagged nine applications in this category, but only seven transmitted the raw IMEI without mentioning such practice in the EULA.

† To the best of our knowledge, the binary messages contained tainted location data (see the discussion below).

Flume

- Extends linux with process-level information flow control
- User-level implementation
- No new OS, can use existing communication abstractions

Flume Labels

- Lattice of labels
  - Label summarizes which categories of data a process is assumed to have seen.
  - Examples:
    - { “Financial Reports” }
    - { “HR Documents” }
    - { “Financial Reports” *and* “HR Documents” }

“tag”

“label”

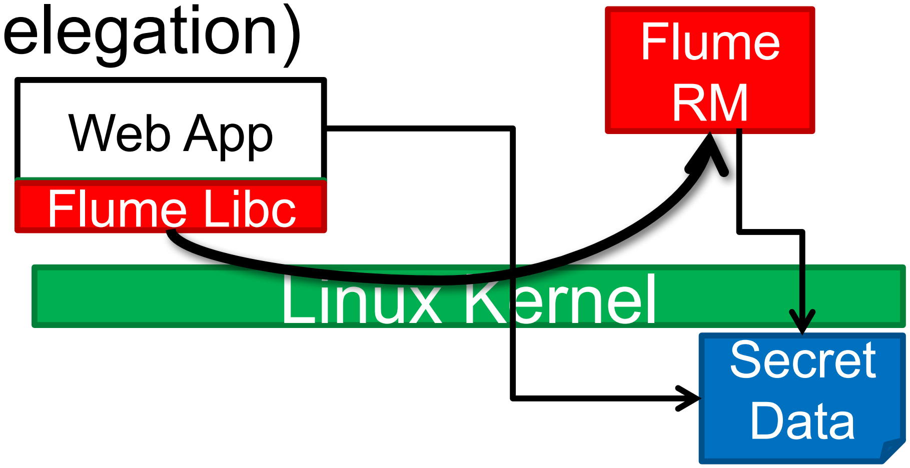
- Processes have an integrity label and a confidentiality label
  - Processes can upgrade their labels
  - Processes can create new tags, can declassify tags they created
  - Inter-process communication mediated by Flume to enforce IFC

Information Flow Control in Flume

- Linux processes communicate via a variety of channels: sockets, pipes, shared memory
- Endpoint abstraction: process can specify which privileges can be used when communicating through each endpoint

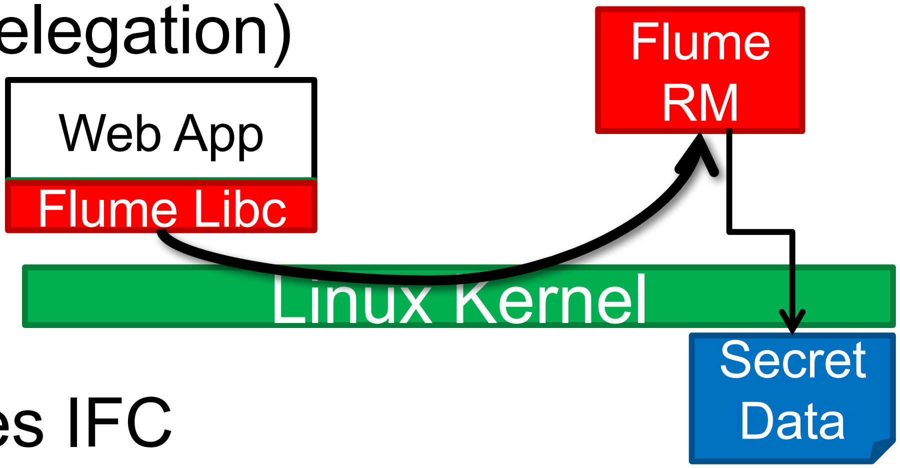
Information Flow Control in Flume

- Linux processes communicate via a variety of channels: sockets, pipes, shared memory
- Endpoint abstraction: process can specify which privileges can be used when communicating through each endpoint
- Flume mediates all communications between endpoints (system call delegation)

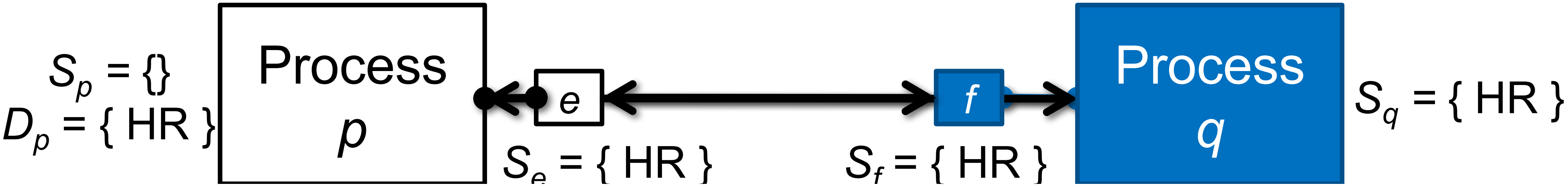


Information Flow Control in Flume

- Linux processes communicate via a variety of channels: sockets, pipes, shared memory
- Endpoint abstraction: process can specify which privileges can be used when communicating through each endpoint
- Flume mediates all communications between endpoints (system call delegation)



- Flume enforces IFC



Limitations

- Dynamic IFC mechanisms incur run-time overhead
  - 30-40% reduction in throughput for file I/O
  - Increased latency
- Large trusted computing base
- Coarse granularity
- Alternative solutions:
  - Dedicated OS (e.g., Asbestos, HiStar)
  - PL-level techniques (e.g., DLM, TaintDroid)

Past and current research on static analysis

- [Denning and Denning 1977]
- VSI type system [Volpano, Smith, and Irvine 1996]
- Jif [Myers 1999] Java + Information Flow (originally JFlow)
- FlowCaml [Simonet 2003] OCaml + Information Flow
- Aura, PCML5, Fine, ...

Jif

```
class passwordFile authority(root) {
    public boolean
      check (String user, String password)
      where authority(root) {
        // Return whether password is correct
        boolean match = false;
        try {
            for (int i = 0; i < names.length; i++) {
                if (names[i] == user &&
                passwords[i] == password) {
                    match = true;
                    break;
                }
            }
        }
            catch (NullPointerException e) {}
            catch (IndexOutOfBoundsException e) {}
        return declassify(match, {user; password});
    }
    private String [ ] names;
    private String { root: } [ ] passwords;
}
```

Jif

```
class passwordFile authority(root) {
    public boolean
      check (String user, String password)
      where authority(root) {
        // Return whether password is correct
        boolean match = false;
        try {
            for (int i = 0; i < names.length; i++) {
                if (names[i] == user &&
                passwords[i] == password) {
                    match = true;
                    break;
                }
            }
        }
            catch (NullPointerException e) {}
            catch (IndexOutOfBoundsException e) {}
        turn declassify(match, {user; password});
    }
    private St   g [ ] names;
    private String { root: } [ ] passwords;
}
```

Security type: only **root** may learn information in this field

Jif

```
class passwordFile authority(root) {
  public boolean
    check (String user, String password)
    where authority(root) {
      // Return whether password is correct
      boolean match = false;
      try {
        for (int i = 0; i < names.length; i++) {
          if (names[i] == user &&
          passwords[i] == password) {
            match = true;
            break;
          }
        }
      }
        catch (NullPointerException e) {}
        catch (IndexOutOfBoundsException e) {}
      return declassify(match, {user; password});
  }
  private String [ ] names;
  private String { root: } [ ] passwords;
}
```

Declassification: okay to leak whether password matches

Jif type checking

- Variables (fields, methods, etc.) may have additional label as part of their type, e.g., `int {lbl} x;`
- Label constrains information flow to and from variable
  - **reader label**: `alice -> bob, charlie`
    - Alice owns this constraint; her permission required to violate it
    - Alice permits the information to flow **to** Bob and Charlie
    - On previous slide: `root:` is short for `root -> root`
  - **writer label:** `alice <- bob, charlie`
    - Alice owns this constraint; her permission required to violate it
    - Alice permits the information to flow **from** Bob and Charlie
  - can have multiple such constraints as part of label
  - can read these arrows as the may flow relation →
  - **Decentralized label model (DLM)** [Myers and Liskov 1997]