Software Security
Information Flow
(Chapter 5 of the lecture notes)

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Motivating example

Imagine using a mobile phone app to

1. locate nearest hotel using google
2. book a room with your credit card

Sensitive information?

- location information
- credit card no

(Un)wanted information flows?

- location may be leaked to google *only*
- credit card info may be leaked to hotel *only*

Can we prevent this by access control on the mobile phone app?

No. The app has access to certain information or not, what it does with this we can not (readily) restrict with access control

Information Flow

- An interesting category of security requirements is about information flow. Eg
  - no confidential information should leak over network
  - no untrusted input from network should leak into database
- Information flow properties can be about confidentiality or integrity
- Note the difference with access control:
  - access control is about *access only*

    (eg for mobile phone app, access to the location data)
  - information flow is *also* about *what you do with data after you accessed it* (eg location obtained from this data)

- Warning: possible exam questions coming up!

Example Information Flow - Confidentiality

```
String hi; // security label secret
String lo; // security label public
```

Which program fragments (may) cause problems if **`hi`** has to be kept confidential?

```
1. hi = lo;
2. lo = hi;
3. lo = "1234";
4. hi = "1234";
```

```
5. println(lo);
6. println(hi);
7. readln(lo);
8. readln(hi);
```

Example Information Flow - Confidentiality

```
String hi; // security label secret
String lo; // security label public
```

Which program fragments (may) cause problems if **hi** has to be kept confidential?

```
✓ 1. hi = lo;
✗ 2. lo = hi;
✓ 3. lo = "1234";
? 4. hi = "1234";
```

```
✓ 5. println(lo)
✗ 6. println(hi);
✓ 7. readln(lo);
? 8. readln(hi);
```

Example Information Flow - *Integrity*

```
String hi; // high integrity (trusted) data
String lo; // low integrity (untrusted) data
```

Which program fragments (may) cause problems if integrity of hi is important ?

```
1. hi = lo;
2. lo = hi;
3. lo = "1234";
4. hi = "1234";
```

```
5. println(lo);
6. println(hi);
7. readln(lo);
8. readln(hi);
```

Example Information Flow - *Integrity*

```
String hi; // high integrity (trusted) data
String lo; // low integrity (untrusted) data
```

Which program fragments (may) cause problems if integrity of hi is important ?

```
✗ 1. hi = lo;            ✓ 5. println(lo);
✓ 2. lo = hi;            ✓ 6. println(hi);
✓ 3. lo = "1234";        ✓ 7. readln(lo);
✓ 4. hi = "1234";        ✗ 8. readln(hi);
```

Duality between integrity & confidentiality

Integrity and confidentiality are ***DUALS:***

if you "flip" everything in a property or an example for confidentiality,

you get a corresponding property or example for integrity

For example

inputs are dangerous for integrity,
outputs are dangerous for confidentiality

Information flow

- Information flow properties are about ruling out unwanted influences/dependencies/interference/observations

- Note the difference between data flow properties and visibility modifiers (eg public, private) or, more generally, access control
  - it's not (just) about accessing data, but also about what you do with it

Questions

- What do we mean by information flow? (informally)
- How can we specify information flow policies?
- How can we enforce or check them?
  - dynamically (runtime)
  - statically (compile time) – by type systems
- What is the semantics (ie. meaning) of information flow formally?

Trickier examples for confidentiality

```
int hi; // security label secret
int lo; // security label public
```

Which program fragments (may) cause problems for confidentiality?

```
1. if (hi > 0) { lo = 99; }
2. if (lo > 0) { hi = 66; }
3. if (hi > 0) { print(lo);}
4. if (lo > 0) { print(hi);}
```

Trickier examples for confidentiality

```
int hi; // security label secret
int lo; // security label public
```

Which program fragments (may) cause problems for confidentiality?

```
✗ 1. if (hi > 0) { lo = 99; }
✓ 2. if (lo > 0) { hi = 66; }
✗ 3. if (hi > 0) { print(lo);}
✗ 4. if (lo > 0) { print(hi);}
```

implicit
aka
indirect flows

indirect vs direct flows

There are (at least) two kinds of information flows

- direct or explicit flows

  by "direct" assignment or leak

  eg `lo=hi;` or `println(hi);`

- indirect or implicit flows

  by indirect "influence"

  eg `if (hi > 0} { lo = 99; }`

Implicit flows can be partial, ie leak some but not all info

(the example above only leaks the sign of **`hi`**, not its value)

Trickier examples for confidentiality

Example

```
int hi; // security label secret
int lo; // security label public
```

Which program fragments (may) cause problems for confidentiality?

```
1. while (hi>99) do {....};
2. while (lo>99) do {....};
3. a[hi] = 23; // where a is high/secret
4. a[hi] = 23; // where a is low/public
5. a[lo] = 23; // where a is high/secret
6. a[lo] = 23; // where a is low/public
```

Trickier examples for confidentiality

```
   int hi; // security label secret
   int lo; // security label public
✗ 1. while (hi>99) do {....};
      // timing or termination may reveal if hi > 99
✓ 2. while (lo>99) do {....}; // no problem
✗ 3. a[hi] = 23; // where a is high/secret
      // exception may reveal if hi is negative
✗ 4. a[hi] = 23; // where a is low/public
      // contents of a may reveal value of hi and, again,
      // exception may reveal if hi is negative
✗ 5. a[lo] = 23; // where a is high/secret
      // exception may reveal the length of a, which may be secret
✓ 6. a[lo] = 23; // where a is low/public – no problem
```

Hidden channels

More subtle forms of indirect information flows can arise via hidden or covert channels, eg

- (non)termination

  eg `while (hi>99) do {....};`

  or `if (hi=99) then {"loop"} else {"terminate"}`

- execution time

  eg `for (i=0; i<hi; i++) {...};`

  or `if (hi=1234) then {...} else {...}`

- exceptions

  eg `a[i] = 23` may reveal length of a (if i is known),

  or leak info about **`i`** (if length of a is known),

  or reveal if a is null..

How can we *statically* enforce information flow policies by means of a type system?

Type-based information flow

Type systems have been proposed as way to restrict information flow.

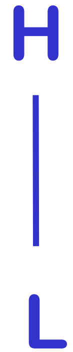
- most of the theoretical work considers confidentiality, but the same works for integrity

Practical problem: often very (too) restrictive, because of difficulty in ruling out implicit flows

Types for information flow (confidentiality)

- We consider a lattice (Dutch: tralie) of different security levels

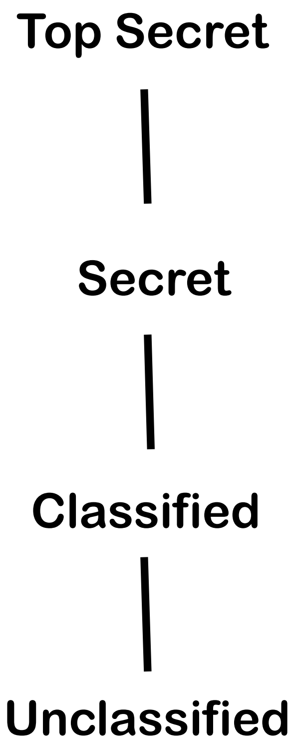
- For simplicity, just two levels
  - H(igh) or confidential, secret
  - L(ow) or public

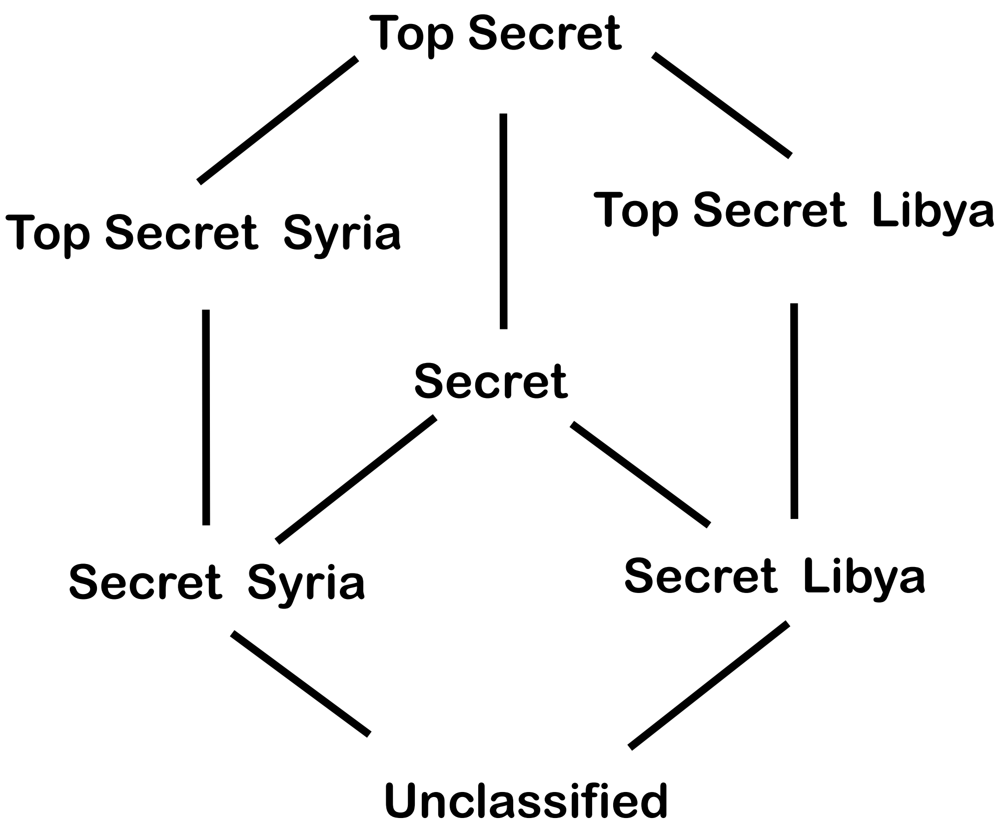


- Typing judgements e:t
  meaning e has type t

- implicitly with respect to a context $x_1:t_1, \ldots x_n:t_n$ that gives levels of program variables

More complex lattices





NATO classification

Cosmic

Secret

Confidential

Restricted

Unclassified

Rules for expressions

e : t means e contains information of level t or *lower*

- variable x:t if x is a variable of type t

- operations
$$\frac{e:t \qquad e':t}{e+e' : t}$$
for some binary operation +
similar for n-ary

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

where L ≤ H

Rules for commands

s : ok t means s only writes to level t or *higher*

- assignment

$$\frac{e : t \qquad x \text{ is a variable of type } t}{x := e \ : ok\ t}$$

- if-then-else

$$\frac{e : t \qquad c1 : ok\ t \qquad c2 : ok\ t}{\text{if } e \text{ then } c1 \text{ else } c2 : ok\ t}$$

subtyping

$$\frac{c : ok\ t \qquad t \geq t'}{c : ok\ t'}$$

ie. ok $t \leq$ ok t' iff $t \geq t'$ (anti-monotonicity)

Rules for commands

s : ok t means s only writes to level t or *higher*

- composition

$$\frac{c1 : ok\ t \qquad c2 : ok\ t}{c1;c2 : ok\ t}$$

- while

$$\frac{e : t \qquad c : ok\ t}{while\ e\ do\ c\ : ok\ t}$$

Beware

Beware of the confusing difference in directions

e : t means e contains information of level t or *lower*

s : ok t means s only writes to level t or *higher*

For people familiar will the Bell – LaPadula access control :
there you have the same confusion,
in the “no read up” & “no write down” rules

How can we be sure that such type systems are “correct”?

Soundness and Completeness

- soundness of the type system:
  programs that are well-typed do no leak
- completeness of the type system:
  programs that do not leak can be typed

Is the type system on preceding slides

- *sound?*
- *complete?*

How can we determine this?

Counterexamples for completeness

It is easy to give examples that are not typable but do not leak, eg

- `if (false) then { lo = hi; }`
- `lo = hi + 1 - hi;`
- `lo = hi; lo = 12;`

Soundness

- Is this type system sound?
  - ie does is prevent the information flows that we want to prevent
- How do we define what we want to prevent?
  - Recall the tricky examples of implicit flows
- This is commonly done using notions of non-interference, which try to capture the notion of what can be observed

  Non-interference gives a precise semantics for what “information flow” means

Soundness wrt non-interference

Definition For memories (or program states) **μ** and **v**, we write

$\mu \approx_L v$ iff **μ** and **v** agree on low variables.

Definition (Non-interference)

A program C does not leak information if, for all $\mu \approx_L v$:

if executing C in **μ** terminates and results in **μ**',

and executing C in **v** terminates and results in **v',**

then $\mu' \approx_L v'$

Theorem (Soundness)

if C : ok t then C does not leak information

Termination as covert channel?

Definition (Non-interference) termination-*in*sensitive

A program C does not leak information if, for all **$\mu \approx_L v$:**

if executing C in **μ** terminates and results in **μ'**,

and executing C in **v** terminates and results in **v',**

then **$\mu' \approx_L v'$**

Does this rule out (non) termination as hidden channel (as observation to distinguish two runs)?

Definition (Termination-sensitive non-interference)

A program C does not leak information if, for all **$\mu \approx_L v$:**

if executing C in **μ** terminates in **μ'**,

then executing C in **v** also terminates, and results in some **v'** with **$\mu' \approx_L v'$**

While-rule for termination-sensitive non-interference

The while-rule

$$\frac{e : t \qquad c : ok\ t}{\text{while } e \text{ do } c : ok\ t}$$

does *not* rule out non-termination as covert channel

A more restrictive rule

$$\frac{e : L \qquad c : ok\ L}{\text{while } e \text{ do } c : ok\ L}$$

does rule this out.

(How? NB this is very restrictive!)

- A similar change needed for in-then-else rule.

Other notions of secure information flow

Other definitions of what it means to be secure (in the sense of non-leaking) are needed if

- if programs can throw exceptions
  - exceptions are another covert channel, just like non-termination
- if programs are multi-threaded or non-determinisitic
  - because execution of a program can then result in several outcomes
    - multi-threaded programs are non-deterministic, because results can depend on scheduling

Information flow for non-deterministic programs

Definition (Possibilistic NI)
A non-deterministic program C does not leak information if
for all $\boldsymbol{\mu} \approx_L \mathbf{v}$
if executing C in $\boldsymbol{\mu}$ terminates in $\boldsymbol{\mu}'$,
then executing C in $\mathbf{v}$ *can* terminate in some $\mathbf{v}'$ with $\boldsymbol{\mu}' \approx_L \mathbf{v}'$

This still ignores probabilistic information flows, for which one would take the *probability* that c terminates in some $\mathbf{v}'$ with $\boldsymbol{\mu}' \approx_L \mathbf{v}'$ into account

- At attacker that can run the program multiple times, might be able to observe something

.

The problem with secure information flow

- *Practical* problem with secure information flow: the extreme restrictions it imposes, esp. when it come to ruling out implicit flows
  - eg no while loop with a high guard
  - note that login program leaks information about the password

- More generally, some way of allowing forms of declassification is needed in practice

Declassification

More *permissive* forms of information flow can allow de-classification, eg

- for confidentiality:
  - output of encryption operation is labelled as public, even though it depends on secret data.
- for integrity:
  - output of input validation routine may be trusted, even though it depends on untrusted data
  - output of routine that checks digital signature may be trusted, even though it depends on untrusted data

Information Flow in "practice"- *static* enforcement

- Many code analysis tools perform some data flow analysis
  - Eg to spot SQL injection problems (as Fortify does)
  - Recall PREfast did this, but only intra-procedural
  - NB typically for integrity, not confidentiality
  - Often unsound/incomplete, as concession to practicality

Information Flow in "practice“- *dynamic* enforcement

- Perl has an *runtime monitoring* of information flow properties (again for integrity properties) using tainting

- Detecting exploits at operating system level

  (eg. worms or viruses that use classic buffer overflows)

  Approach:

  1. taint user input,
  2. trace this during execution,
  3. warn if tainted input ends up on
     - the instruction register or program counter of CPU
     - in a function pointer
     - ...

  This can detect zero-day exploits, and be used to prove that something is an exploit. But is kills performance...

Information Flow in "practice“

Pragmatic approaches typically worry less – if at all - about implicit flows.

Indeed, are implicit flows an issue for integrity?

Related work: Bell-La Padula

- Classic Bell-La Padula system access control combines
  - Mandatory Access control (MAC)
  - Multi-Level Security (MLS)

  and protects information flow between files by rules
  - no read up
  - no write down
    - *nb similarity with our typing rules b*ut for processes accessing files, instead of a programs accessing variables, and enforced at runtime instead of compile time
- Bell-LaPaluda was developed in the 70s for access control in military applications

Summary

- What is information flow (informally)?
  - explicit flows , implicit flows, covert channels
- How can we *statically* control information flow, using type systems?
- How can we formally define what information flow is?

  non-interference

  termination sensitive vs termination insensitive

You can read all this in Chapter 5 of the lecture notes

Possible exam questions

- Explaining if there is unwanted information for integrity or confidentiality in example programs (like those on slides 5, 7, 12, 15)
- Giving and/or motivating a typing rule for information flow typing (like on slides 23-25 or 33), for termination-sensitive or insensitive
- Giving and/or explaining the definition of non-interference, for integrity or confidentiality (but not the possibilistic & probabilistic versions)