463.8 Information Flow

Computer Security II
CS463/ECE424
University of Illinois

Security News of the Day

https://www.nytimes.com/2021/09/16/technology/digital-privacy.html

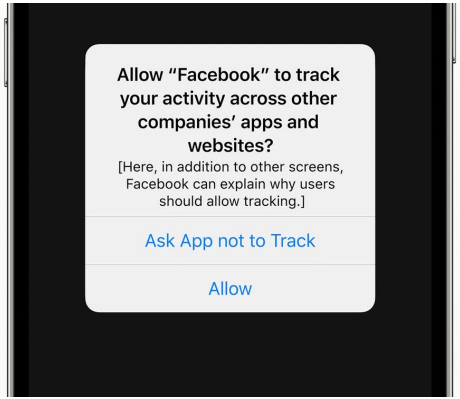
The New York Times

The Battle for Digital Privacy Is Reshaping the Internet

SAN FRANCISCO — Apple introduced a pop-up window for iPhones in April that asks people for their permission to be tracked by different apps.

Google recently outlined plans to disable a tracking technology in its Chrome web browser.

And Facebook said last month that hundreds of its engineers were working on a new method of showing ads without relying on people's personal data.



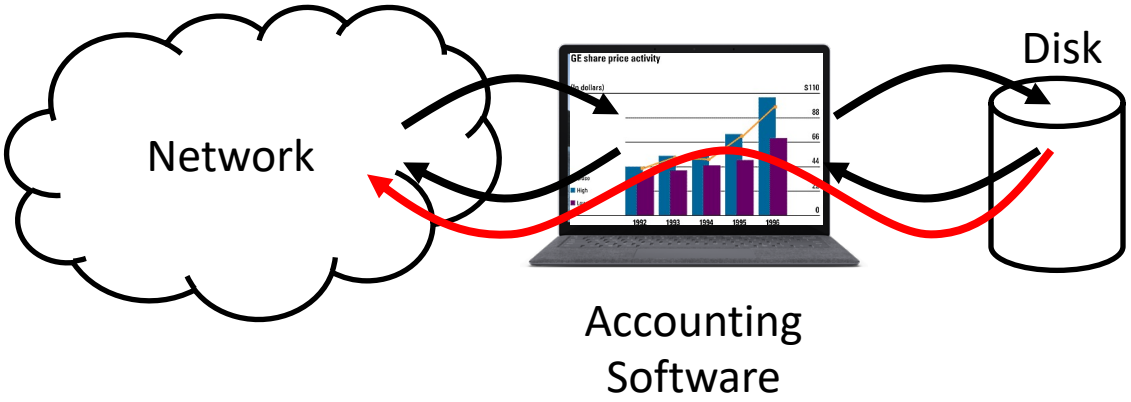
Businesses that do not keep up with the changes risk getting run over. Increasingly, media publishers and even apps that show the weather are charging subscription fees, in the same way that Netflix levies a monthly fee for video streaming. Some e-commerce sites are considering raising product prices to keep their revenues up.

Information Flow
Formal Model (two classic papers)

[GoguenM82J Security Policies and Security Models, J. A. Goguen and J. Meseguer. IEEE Security and Privacy 1982.
[DenningD77] Certification of Programs for Secure Information Flow, Dorothy E. Denning and Peter J. Denning. CACM 20(7), 1977.

Example: Financial Planner

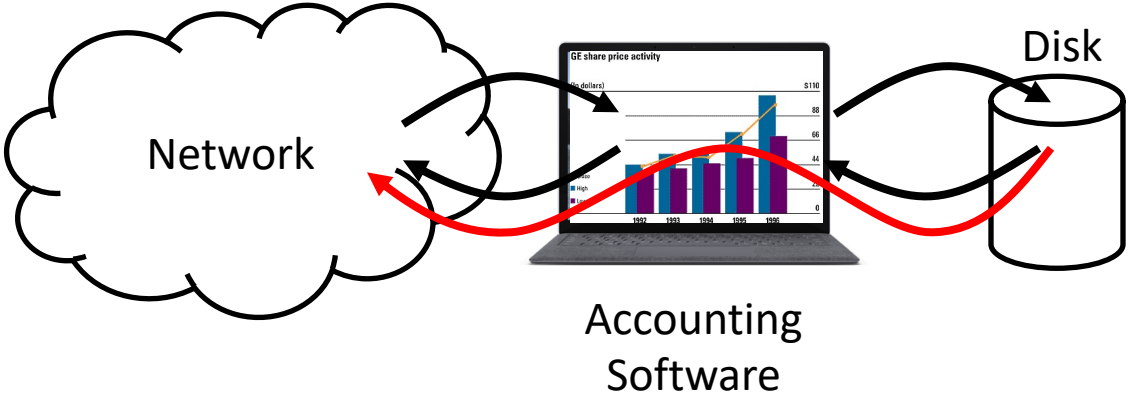
- Downloadable financial planner software:



- Access control insufficient
- Encryption necessary, but also insufficient

Noninterference

- Downloadable financial planner software:



  - Private data does not *interfere* with network communication
  - Baseline confidentiality policy

Example: Payment Card for For Financial Transactions

- Card contains sensitive financial info used to make a transaction
- Used in the terminal of a merchant
- Card is tamper-resistant, protects card secrets from both the merchant and card holder
- Java cards provide limited card-based computation
- Must split the computation between the card, the terminal, and network connections

Model of Noninterference

- Represent noninterference as a relation between groups of users and commands
- Users in group G do not interfere with those in group G' if the state seen by G' is not affected by the commands executed by members of G
- Example: hotel rooms
  - Infer people's activities based on side channels

[GoguenM82J Security Policies and Security Models, J. A. Goguen and J. Meseguer. IEEE Security and Privacy 1982.

State Automaton

- U – Users
- S – States
- C – Commands
- Out – Outputs
- $do : S \times U \times C \rightarrow S$ – state transition function
- $out : S \times U \rightarrow Out$ – output function
- s_0 – initial machine state

Capability System

- U, S, Out – users, states, commands, and outputs as before
- SC – State commands
- Capt – Capability tables (*defines permissions available to users*)
- CC – Capability commands
- out : $S \times Capt \times U \rightarrow Out$
- do : $S \times Capt \times U \times SC \rightarrow S$
- cdo : $Capt \times U \times CC \rightarrow Capt$ – Capability selection function
  - Give users a new permission or update the users' permissions
- $s_0 \in S$ and $t_0 \in Capt$ – Initial state and capability tables

Transition Function

- $C = SC \uplus CC$ - Commands
- $csdo : S \times Capt \times U \times C \rightarrow S \times Capt$
  - $csdo(s,t,u,c) = (do(s,t,u,c),t)$ if $c \in SC$
  - $csdo(s,t,u,c) = (s,cdo(s,t,u,c))$ if $c \in CC$
- $csdo^* : S \times Capt \times (U \times C)^* \rightarrow S \times Capt$
  - $csdo^*(s,t,nil) = (s,t)$
  - $csdo^*(s,t,w.(u,c)) = csdo(csdo^*(s,t,w),u,c)$
- $[[w]] = csdo^*(s_0,t_0,w)$
- $[[w]]_u = out([[w]],u)$

Chaining

Output the states visible to user u

Projection

- Let $G \subseteq U$ and $A \subseteq C$ and $w \in (U \times C)^*$
- $P_G(w)$ = subsequence of w obtained by eliminating pairs (u,c) where $u \in G$
- $P_A(w)$ = subsequence of w obtained by eliminating pairs (u,c) where $c \in A$
- $P_{G,A}(w)$ = subsequence of w obtained by eliminating pairs (u,c) where $u \in G$ and $c \in A$

Define Noninterference G :| G′

G does not interferer with G′

- M state machine and G, G’ ⊆ U and A ⊆ C
- G :| G’ iff $\forall$ w $\in$ (U × C)*. $\forall$ u $\in$ G’. $[[w]]_u = [[p_G(w)]]_u$
- A :| G iff $\forall$ w $\in$ (U × C)*. $\forall$ u $\in$ G. $[[w]]_u = [[p_A(w)]]_u$
- A,G :| G’ iff $\forall$ w $\in$ (U × C)*. $\forall$ u $\in$ G’. $[[w]]_u = [[p_{A,G}(w)]]_u$

Security Policies

- *Noninterference assertions* have the forms

  G :| G’

  A :| G

  A,G :| G’

- A *security policy* is a set of noninterference assertions

Example 1

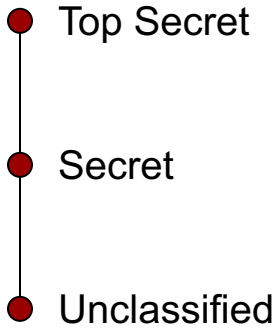
- A :| {u}
- The commands in A do not interfere with the state of user u

Example 2 Multilevel Security (MLS) and BLP Model

Less than or equal to

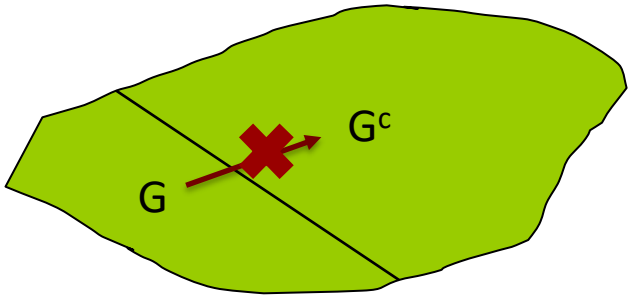
- Level : U $\rightarrow$ L
  - Assignment of security levels in L
- Above(λ) = { u $\in$ U | $\lambda \sqsubseteq$ Level(u)}
- Below(λ) = { u $\in$ U | Level(u) $\sqsubseteq \lambda$}
- M is *multi-level secure* with respect to L if, for all $\lambda \sqsubset \lambda'$ in L, Above(λ') :| Below(λ)

Levels L $\sqsubseteq$



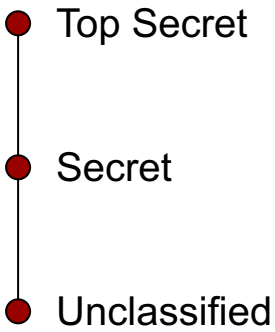
MLS Continued

- G is *invisible* if G :| G^c where G^c is the complement of G in U



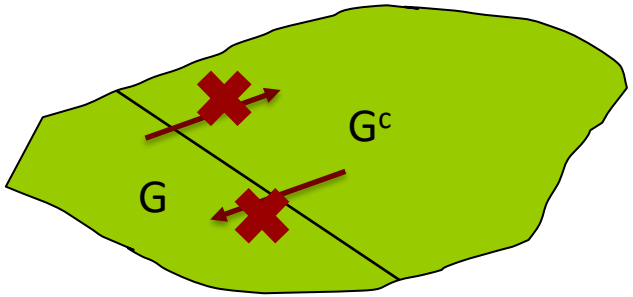
- **Proposition 1**: *If M,L is multi-level secure, then Above(λ) is invisible for every λ ∈ L.*

Levels L ⊑



Example 4 Isolation

- A group of users G is *isolated* if: G :| G^c and G^c :| G.
- A system is *completely* isolated if every user in U is isolated.



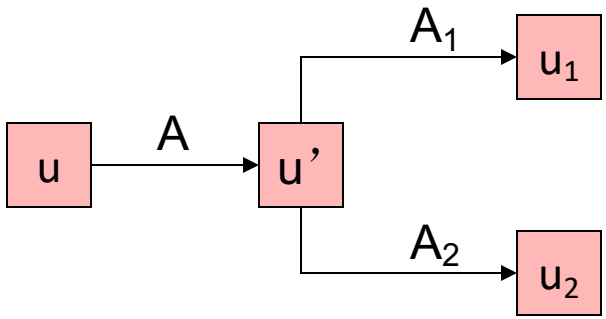
Example 5 Channel Control

- View a *channel* as a set of commands A
- We can assert that groups of users G and G' can only communicate through channel A with the following two noninterference assertions:

$A^c, G :| G'$

$A^c, G' :| G$

Example 6 Information Flow



$u', u_1, u_2 :| u$

$u_1, u_2 :| u'$

$u_1 :| u_2$

$u_2 :| u_1$

$A^c, u :| \{u', u_1, u_2\}$

$A_1^c, u' :| \{u_1\}$

$A_2^c, u' :| \{u_2\}$

Example 7 Security Officer

- Let A be the set of commands that can change the security policy
- seco ∈ U is the only individual permitted to use these commands to make changes
- This is expressed by the following policy: A, $\{seco\}^c$:| U

Entropy and Information Flow

- It is possible to analyze information flows in programs with an information theory foundation

- Intuition: info flows from x to y as a result of a sequence of commands c if you can deduce information about x before c from the value in y after c

$$x \xrightarrow{c} y$$

[DenningD77] Certification of Programs for Secure Information Flow, Dorothy E. Denning and Peter J. Denning. CACM 20(7), 1977. http://seclab.uiuc.edu/docs/DenningD77.pdf

Example 1

- y := x (*assign value x to variable y*)
  - If we learn y, then we know x
  - Clearly information flows from x to y

Example 2

- Suppose we are given

  r := x

  r := r - r

  y := 1 + r
- Does information flow from x to y?
- It does not, because r = 0 after the second command
  - There is no information flowing from x to y

Example 3

- Consider this branching command:

if $x = 1$ **then** $y := 0$
else $y := 1$;

- If we find after this command that y is 0, then we know that x was 1
- So information flowed from x to y

Implicit Flow of Information

- Information flows from x to y without an *explicit* assignment of the form $y := f(x)$ where $f(x)$ an arithmetic expression with variable x
- Recall the example from previous slide:

  if $x = 1$ **then** $y := 0$

  else $y := 1$;
- So we must look for *implicit* flows of information to analyze program

Conservative Automated Analysis of Flow

- Example 2 depends on an arithmetic property of subtraction
  - “r – r = 0”
- It is impossible to take each such property into account when doing an automated analysis
  - Ultimately undecidable
- Hence an automated analysis will be a conservative approximation of information flows
  - All flows can be found (even if trivially!)
  - Some non-flows (false positives) will be found

Compiler-Based Mechanisms

If a variable contains high-security information, does the information leak to low-security variables?

- Detect unauthorized information flows in a program during compilation
- Analysis not precise (may have false positives), but secure
  - If a flow *could* violate policy (but may not), it is unauthorized
  - No unauthorized path along which information could flow remains undetected
- Set of statements *certified* with respect to information flow policy if flows in set of statements do not violate that policy

Example

$\underline{x}$ is the security class of x

```
if x = 1 then y := a else y := b;
```

- Info flows from x and a to y, or from x and b to y
- Certified only if information from the security class $\underline{x}$ of x is allowed to flow into the security class $\underline{y}$ of y and similar conditions hold for a and b relative to y.
- Write: $\underline{x} \leq \underline{y}$ and $\underline{a} \leq \underline{y}$ and $\underline{b} \leq \underline{y}$
  - Note flows for *both* branches must be true unless compiler can determine that one branch will *never* be taken

Declarations

"lub": least upper bound

x: int class {A,B}

- Means x is an integer variable with security class at least lub{ A, B } so lub{ A, B } ≤ <u>x</u>.
- Basic case is two security classes, High and Low.

Assignment Statements

```
x := y + z;
```

- Information flows from y, z to x
- this requires $\text{lub}\{\underline{y}, \underline{z}\} \leq \underline{x}$

More generally:

```
y := f(x1, ..., xn)
```

- Require $\text{lub}\{\underline{x_1}, \ldots, \underline{x_n}\} \leq \underline{y}$

Compound Statements

```
x := y + z;
a := b * c - x;
```

- First statement: lub{$\underline{y}$, $\underline{z}$} ≤ $\underline{x}$
- Second statement: lub{$\underline{b}$, $\underline{c}$, $\underline{x}$} ≤ $\underline{a}$
- So, both must hold (i.e., be secure)

More generally:

S_1; … S_n;

- Each individual S_i must be secure

Iterative Statements

```
while i < n do
begin a[i] := b[i]; i := i + 1; end
```

- Same ideas as for "if", but must terminate

More generally:

```
while f(x1, …, xn) do S;
```

"glb": greatest lower bound

- S must be secure
- $\text{lub}\{\ \underline{x}_1, \ldots, \underline{x}_n\ \} \leq \text{glb}\{\underline{y} \mid y \text{ target of an assignment in } S\}$
- Loop must terminate

Conditional Statements

```
if x + y < z
then a := b
else d := b * c - x; end
```

- The statement executed reveals information about x, y, z, so lub{ $\underline{x}$, $\underline{y}$, $\underline{z}$ } ≤ glb{ $\underline{a}$, $\underline{d}$ }

More generally:

```
if f(x1, …, xn) then S1 else S2; end
```

- S_1, S_2 must be secure
- lub{ $\underline{x}_1, \ldots, \underline{x}_n$ } ≤ glb{$\underline{y}$ | y target of assignment in S_1, S_2 }

```
1  begin
2    i,n: integer security class L;
3    flag: Boolean security class L;
4    f1,f2: file security class L;
5    x,sum: integer security class H;
6    f3,f4: file security class H;
7    begin
8      i := 1;                                   1 → i (L → L)
9      n := 0;                                   0 → n (L → L)
10     sum := 0;                                 0 → sum (L → H)
11     while i ≤ 100 do
12       begin
13         input flag from f1;                   f1 → flag (L → L)
14         output flag to f2;                    flag → f2 (L → L)
15         input x from f3;                      f3 → x (H → H)
16         if flag then
17           begin
18             n := n + 1;                       n ⊕ 1 → n (L → L)
19             sum := sum + x                    sum ⊕ x → sum (H → H)
20           end;                                flag → n ⊗ sum (L → L)
21         i := i + 1                            i ⊕ 1 → i (L → L)
22       end;                                    i ⊕ 100 → flag ⊗ f2 ⊗ x ⊗
                                                   n ⊗ sum ⊗ i (L → L)
23     output n, sum, sum/n to f4                n ⊕ sum ⊕ sum ⊕ n → f4 (H → H)
24   end
25 end
```

Need to Handle More

- Procedures
- Arrays
- Goto Statements
- Exceptions
- Infinite loops
- Concurrency
- Etc

Reading

- [Bishop03] Computer Security Art and Science, Matt Bishop, Addison Wesley, 2003.
  - Chapter 8 up to the beginning of 8.2.1.
  - Chapter 16 sections 16.1 and 16.3
- [GoguenM82J Security Policies and Security Models, J. A. Goguen and J. Meseguer. IEEE Security and Privacy 1982.
- [DenningD77] Certification of Programs for Secure Information Flow, Dorothy E. Denning and Peter J. Denning. CACM 20(7), 1977.

Discussion

Consider the following two case studies.

Case Studies

Audit

Consider the security officer in example 7: seco ∈ U is the only individual permitted to use these commands to make changes

Shouldn't the officer see audit information from the users who attempt to execute security commands?

Secret Communication

A general tells his army that if they see a green flag they should attack from the left but if they see a red flag they should attack from the right.

The general raises the green flag and the enemy forces see this.

Did the signal "interfere" with the enemy?