463.9 Information Flow

CS463/ECE424
University of Illinois

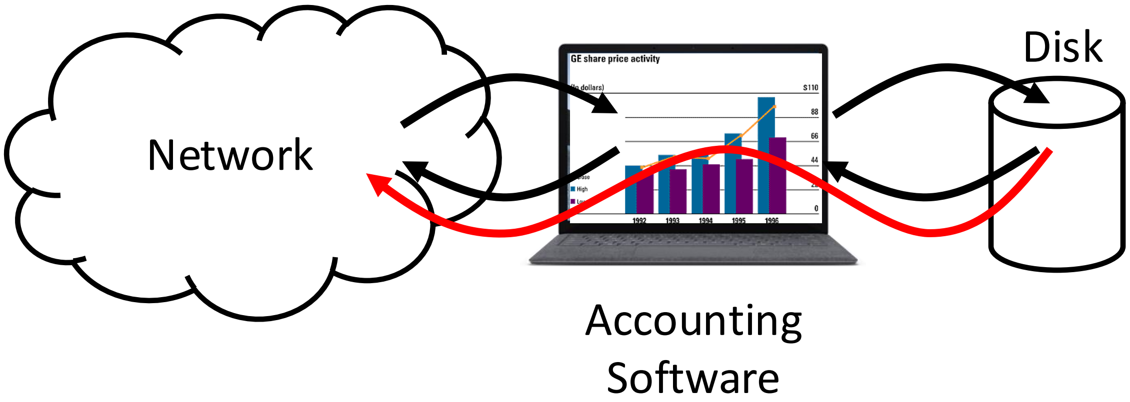
Information Flow
Formal Model (two classic papers)

[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

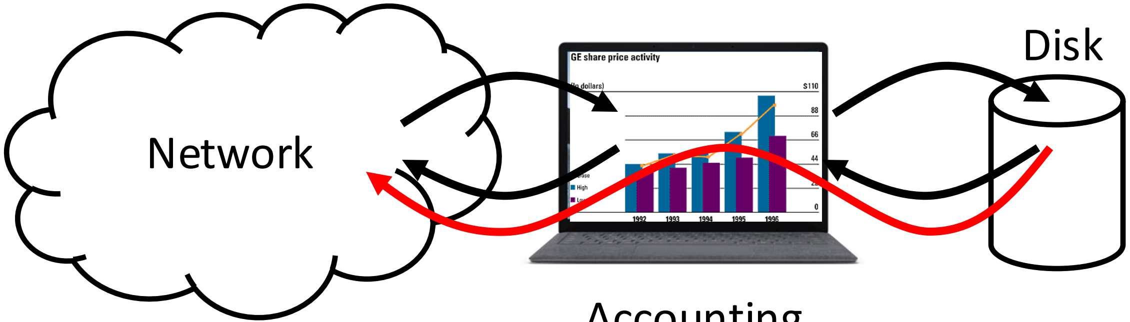
- Downloadable financial planner software:



  - Access control insufficient
  - Encryption necessary, but also insufficient

Noninterference

- Downloadable financial planner software:



Network

Disk

Accounting
Software

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

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
  - What does the user have to “do” to go from state 1 to state 2
- out : $S \times U \rightarrow Out$ – output function
  - What is the “output” the user sees at a particular state
- s_0 – initial machine state

Capability System

- U, S, Out – users, states, commands, and outputs as before
- CapT – Capability tables (*defines permissions available to users*)
  - Not all users are equal!
- **SC** – State commands
- **CC** – Capability commands
- out : S × (CapT × U) → Out
  - (CapT × U) denotes a user with a particular permission level
- do : S × SC × (CapT × U) → S
  - Earlier, we had -- do : S × C × U → S

Capability System: New function

- **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 ⊎ CC - Commands
- **csdo** : $S \times (CapT \times U) \times C \rightarrow S \times CapT$
  - Combining do and cdo
  - csdo(s,t,u,c) = (do(s,t,u,c),t) if c ∈ SC
  - csdo(s,t,u,c) = (s,cdo(s,t,u,c)) if c ∈ CC
- csdo* : $S \times CapT \times \underline{(U \times C)^*} \rightarrow S \times CapT$
  - csdo*(s,t,nil) = (s,t)
  - If w is a sequence of “n” (u,c) i.e.,$(u, c)^n$ then
    - csdo*(s,t,w. (u,c)) = csdo(csdo*(s,t,w),u,c)
- [[w]] = csdo*(s_0,t_0,w) = some (s,t)
- $[[w]]_u$ = out([[w]],u)

Chaining

Output the states visible to user u

Projection

Let $G \subseteq U$ (some users G in U)

and $A \subseteq C$ (some commands in C)

and $w \in (U \times C)^*$ (some sequence of user issued commands)

- $P_G(w)$ = 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 is a state machine and G, G’ $\subseteq$ U and A $\subseteq$ 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: Isolation around User

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

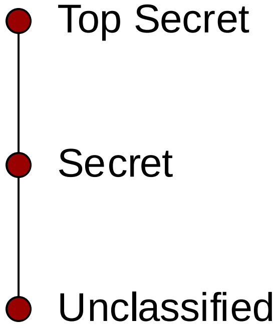
Example 2: Multilevel Security (MLS) and BLP Model

Less than or equal to

Recall: No write down!

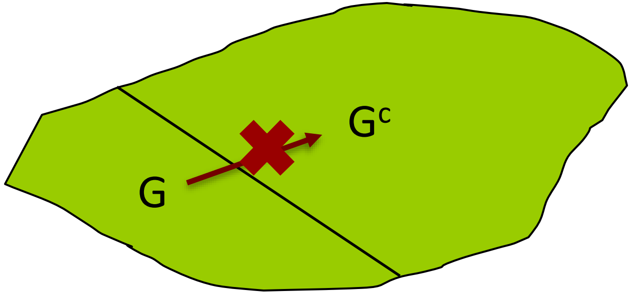
- Define Level : $U \rightarrow L$
  - Assignment of security levels in L
- $\text{Above}(\lambda) = \{ u \in U \mid \lambda \sqsubseteq \text{Level}(u)\}$
- $\text{Below}(\lambda) = \{ u \in U \mid \text{Level}(u) \sqsubseteq \lambda\}$
- M is *multi-level secure* with respect to L if, for all $\lambda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

Levels L $\sqsubseteq$



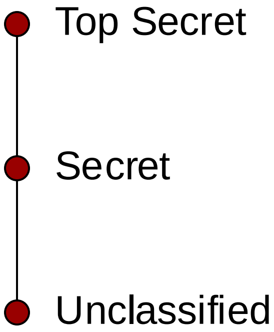
MLS Continued: Invisibility

- 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 ⊑

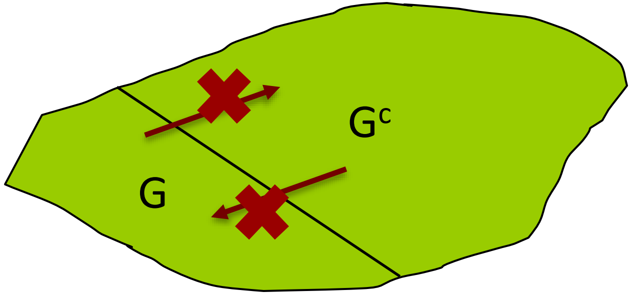

Top Secret

Secret

Unclassified

Example 4: Isolation (Stronger Invisibility)

- 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.



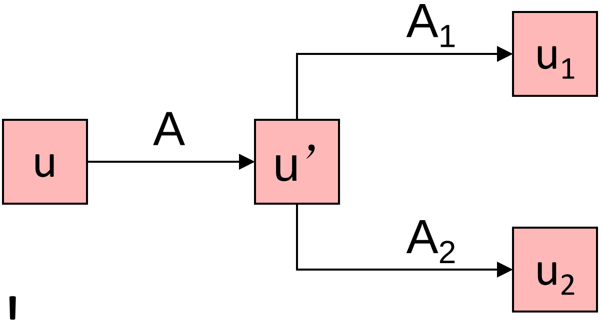
Example 5: Channel Control

- 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’ : commands not in A can’t enable flow b/w G and G’

  A^c,G’ :| G : commands not in A can’t enable flow b/w G’ and G

Example 6: Information Flow



Look backward!!

$u', u_1, u_2 :| u$

$u_1, u_2 :| u'$

$u_1 :| u_2$

$u_2 :| u_1$

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

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

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

Example 7: Security Officer

- Let A be the set of commands that can change the security policy
- seco $\in$ 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*

In class example

```
X = 25
IF SQRT(X) == 5:
    Y = 1
Y= 0
```

```
X = 30
IF SQRT(X) == 5:
    Y = 1
Y= 1
```

```
X = 30
IF SQRT(X) == 5:
    Y = 1
Else:
    Y= 1
```

Logic:	NO	NO	NO
Comp:	NO	NO	YES

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: $\underline{x} \le \underline{y}$ and $\underline{a} \le \underline{y}$ and $\underline{b} \le \underline{y}$
  - 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{ $\underline{A}$, $\underline{B}$ } so lub{ $\underline{A}$, $\underline{B}$ } $\leq$ $\underline{x}$.
- Basic case is two security classes, High and Low.

Assignment Statements

`x := y + z;`

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

More generally:

$\texttt{y := f(x}_1\texttt{, …, x}_n\texttt{)}$

- Require lub{ $\underline{x}_1$, …, $\underline{x}_n$ } ≤ $\underline{y}$

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:

$S_1;\ \ldots\ S_n;$

- 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:

$\texttt{while f(}x_1\texttt{, …, }x_n\texttt{) do S;}$

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

“glb”: greatest lower bound

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$\{ \underline{x}, \underline{y}, \underline{z} \} \leq$ glb$\{ \underline{a}, \underline{d} \}$

More generally:

```
if f($x_1$, …, $x_n$) then $S_1$ else $S_2$; end
```

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

```
begin
  i,n: integer security class L;
  flag: Boolean security class L;
  f1,f2: file security class L;
  x,sum: integer security class H;
  f3,f4: file security class H;
  begin
    i := 1;                                  $\underline{1} \rightarrow \underline{i}\ (L \rightarrow L)$
    n := 0;                                  $\underline{0} \rightarrow \underline{n}\ (L \rightarrow L)$
    sum := 0;                                $\underline{0} \rightarrow \underline{sum}\ (L \rightarrow H)$
    while i ≤ 100 do
      begin
        input flag from f1;                  $\underline{f1} \rightarrow \underline{flag}\ (L \rightarrow L)$
        output flag to f2;                   $\underline{flag} \rightarrow \underline{f2}\ (L \rightarrow L)$
        input x from f3;                     $\underline{f3} \rightarrow \underline{x}\ (H \rightarrow H)$
        if flag then
          begin
            n := n + 1;                      $\underline{n} \oplus \underline{1} \rightarrow \underline{n}\ (L \rightarrow L)$
            sum := sum + x                   $\underline{sum} \oplus \underline{x} \rightarrow \underline{sum}\ (H \rightarrow H)$
          end;                               $\underline{flag} \rightarrow \underline{n} \otimes \underline{sum}\ (L \rightarrow L)$
        i := i + 1                           $\underline{i} \oplus 1 \rightarrow \underline{i}\ (L \rightarrow L)$
      end;                                   $\underline{i} \oplus \underline{100} \rightarrow \underline{flag} \otimes \underline{f2} \otimes \underline{x} \otimes$
                                               $\underline{n} \otimes \underline{sum} \otimes \underline{i}\ (L \rightarrow L)$
    output n, sum, sum/n to f4               $\underline{n} \oplus \underline{sum} \oplus \underline{sum} \oplus \underline{n} \rightarrow \underline{f4}\ (H \rightarrow H)$
  end
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.

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?