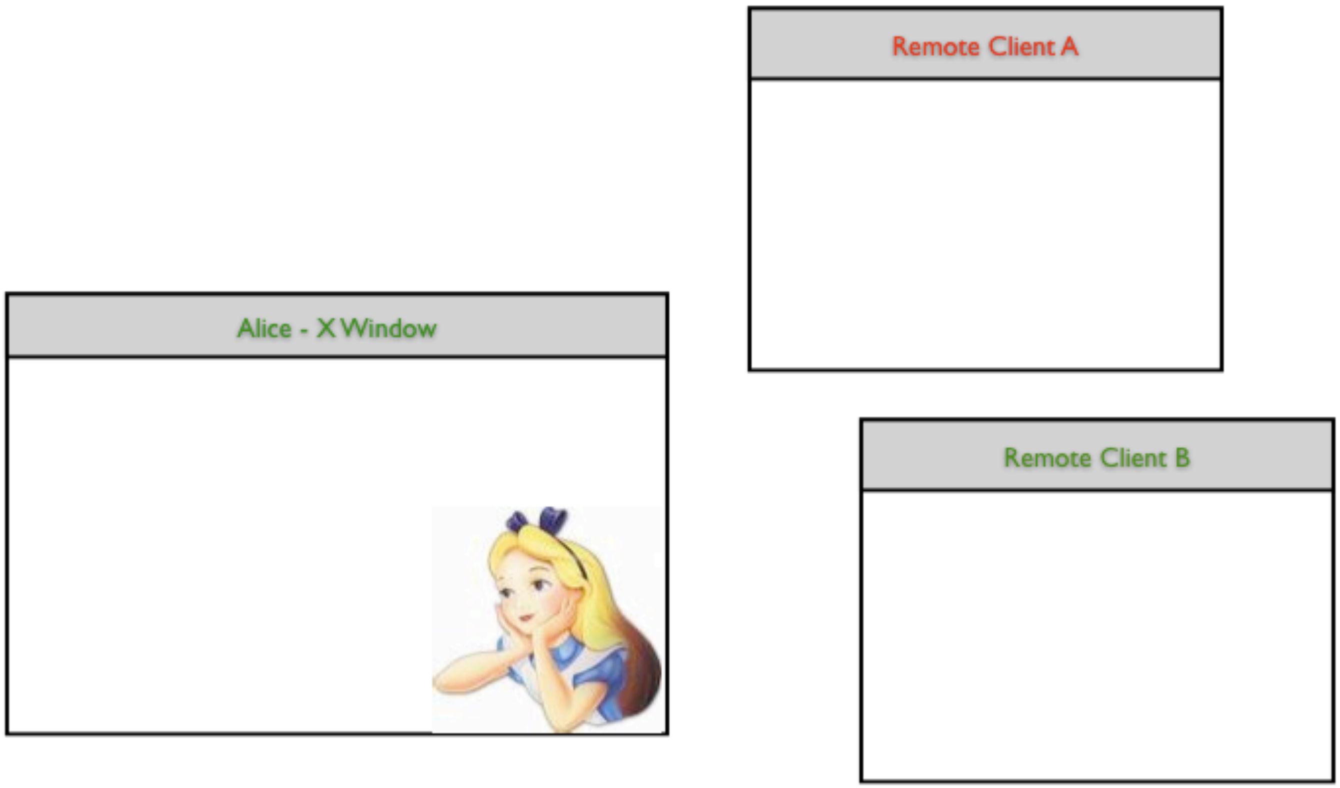
Advanced Systems Security: Program Information Flow Control

Trent Jaeger
Systems and Internet Infrastructure Security (SIIS) Lab
Computer Science and Engineering Department
Pennsylvania State University

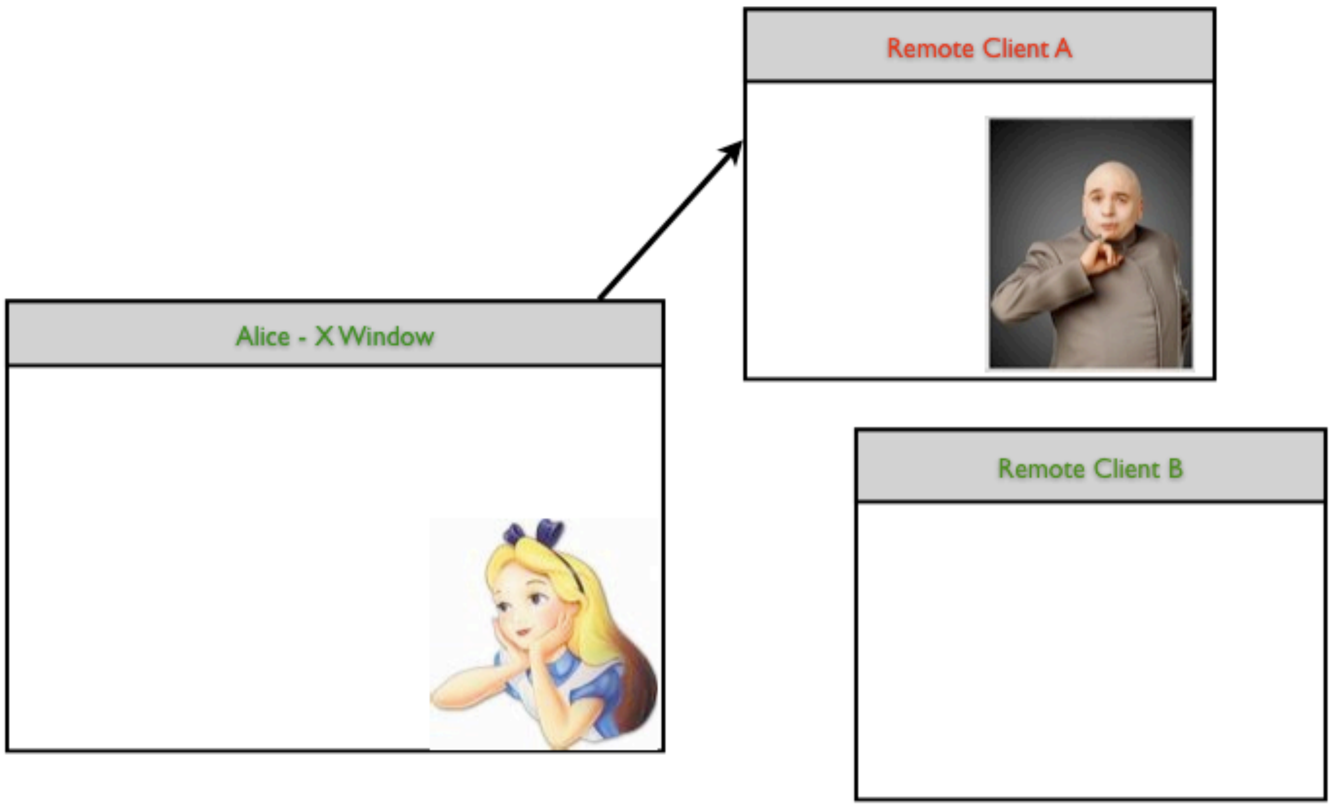
Problem

- A program is trusted to enforce a system's policy
  - How do we know?
- So what can we do?

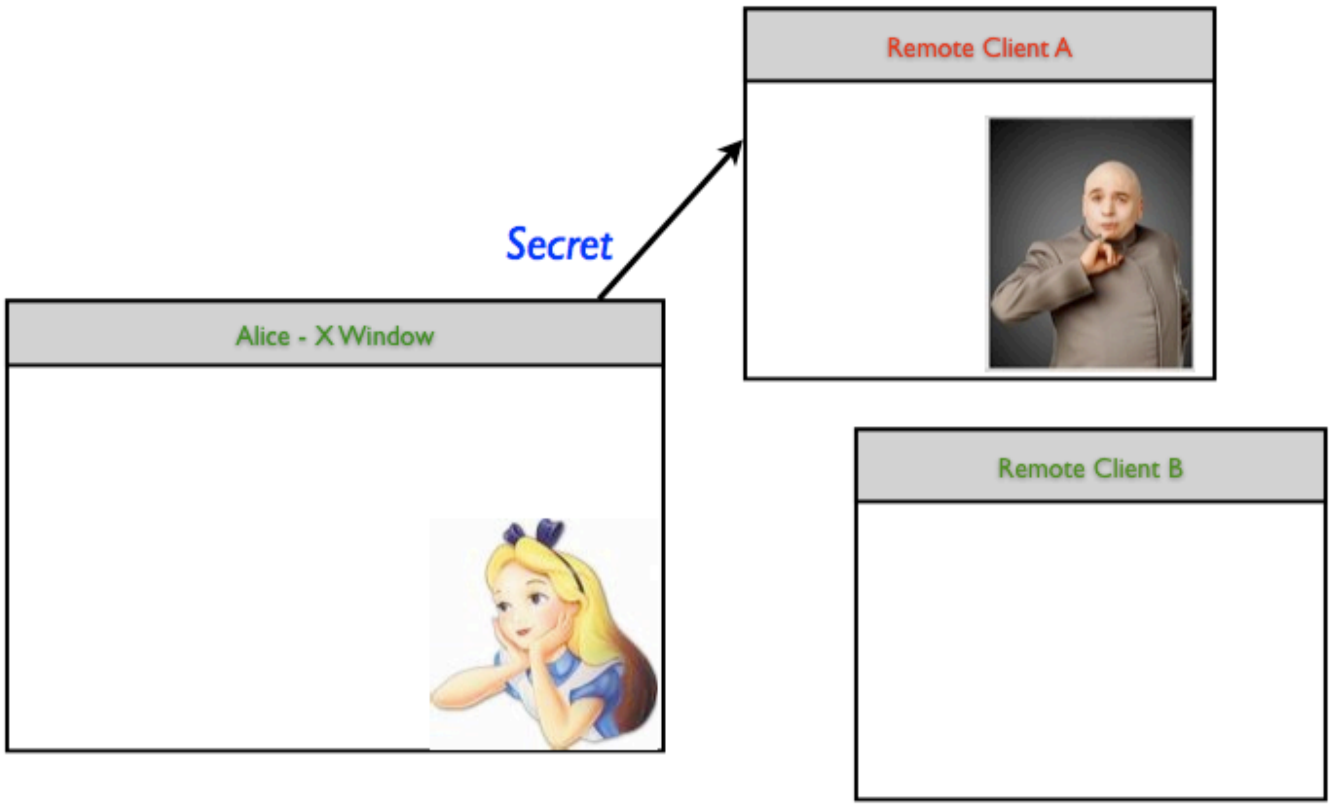
Problem



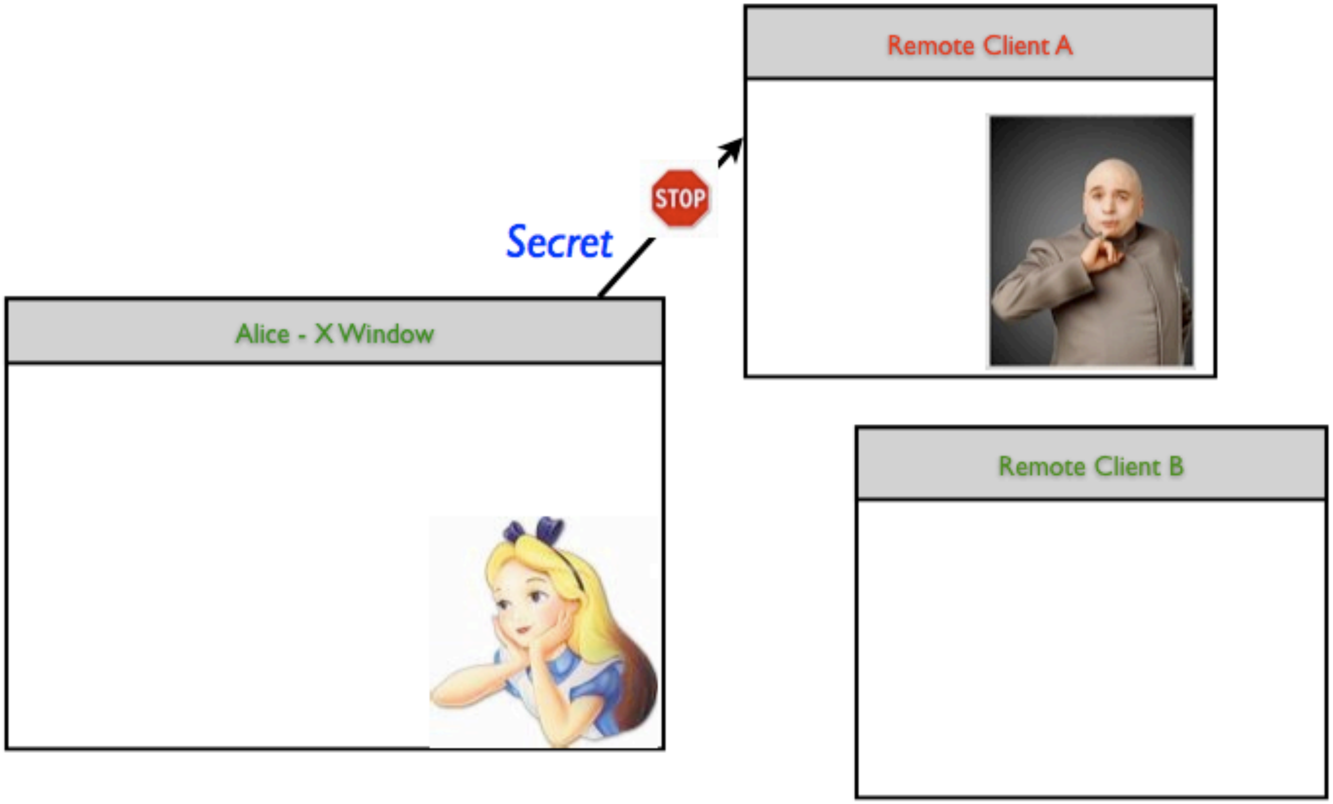
Problem



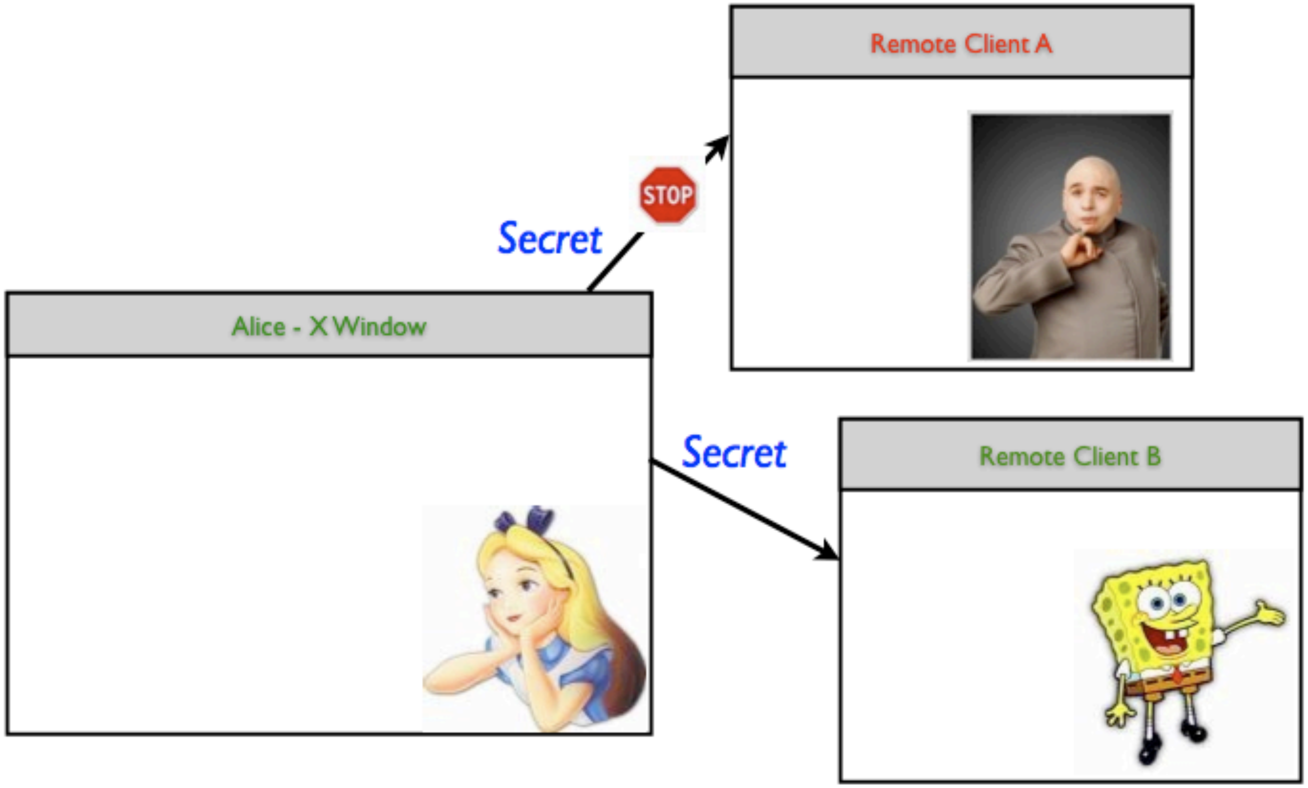
Problem



Problem

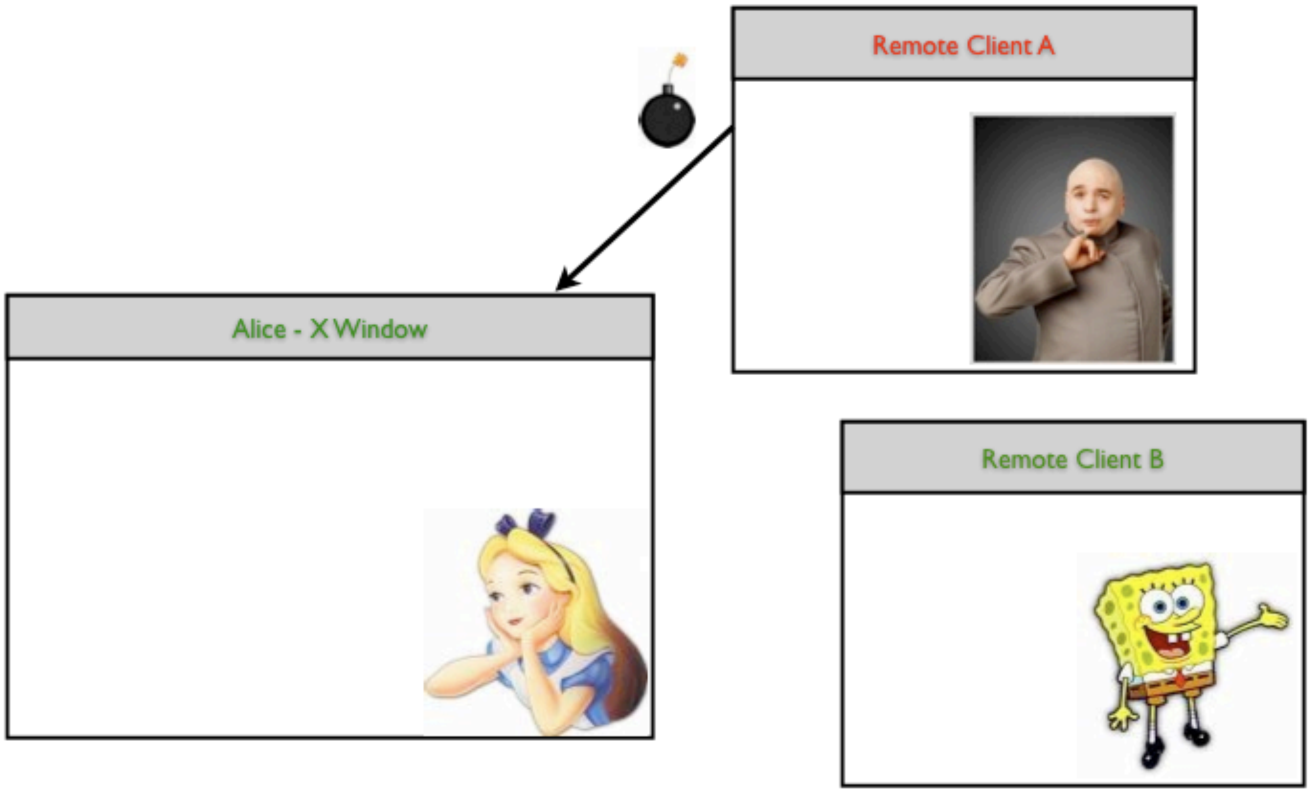


Problem

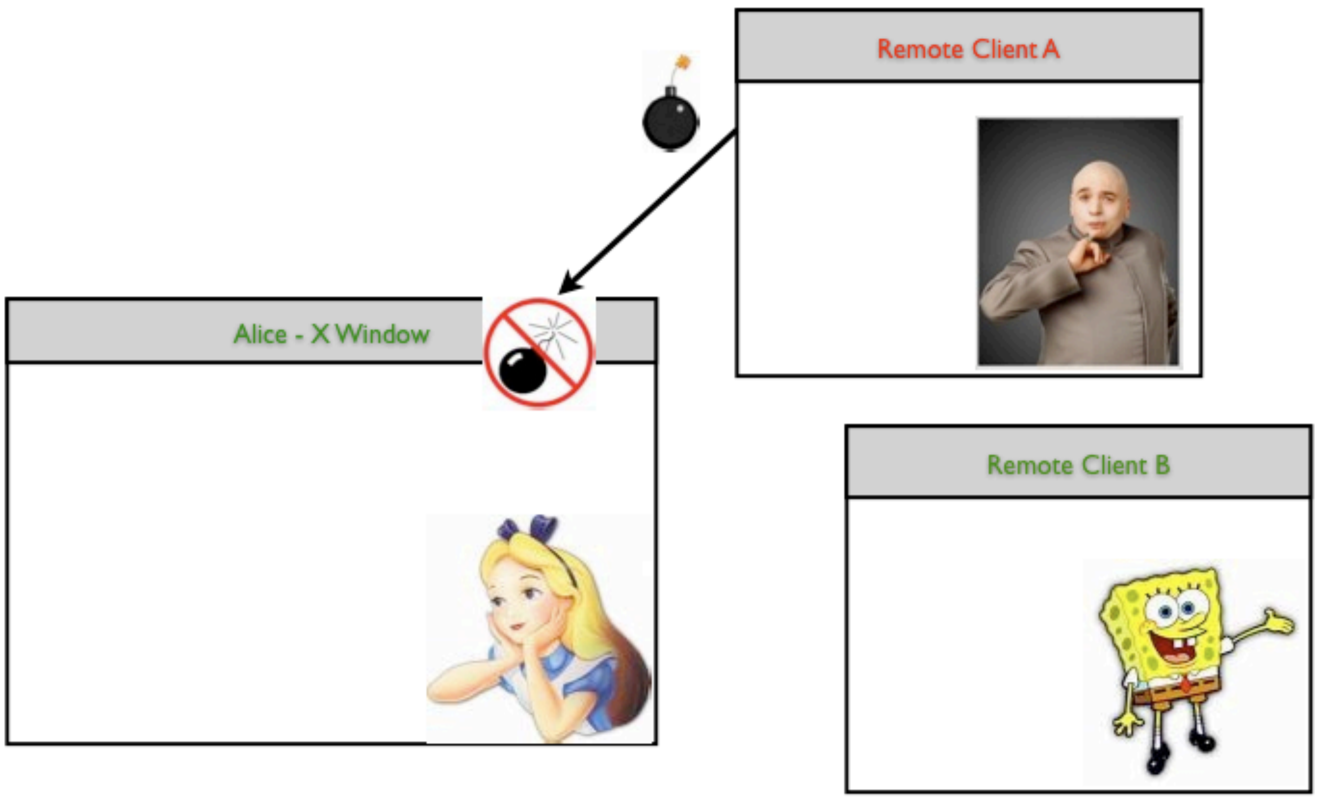


Remote Client A
STOP
Secret
Alice - X Window
Secret
Remote Client B

Problem



Problem



What's a Program?

- Program parts
  - *Statements (Expressions), Variables, Control Statements, Procedures, Arguments, System calls/Library calls*
- What does a program look like from a security perspective?
  - Variables have data (may have secrecy/integrity reqs)
  - Variable values may come from external sources
  - Variable values may be assigned to one another
  - Variables may be written out of the program (sink)

What's a Program?

- **Ensure that secret data is encrypted before it is released.**

```
user_name = getString();
secret_data_1 := getPasswdFromUser();
secret_data_2 := getPasswdFromUser();
If(secret_data_1 == secret_data_2)
    writeToFile(secret_data_1);
else
    writeToOutput("Passwords do not match");
```

What's a Program?

- **Ensure that secret data is encrypted before it is released.**

```
1.user_name = getString();
2.secret_data_1 := getPasswdFromUser();
3.secret_data_2 := getPasswdFromUser();
4.If(secret_data_1 == secret_data_2)
5.    writeToFile(encrypt(secret_data_1));
6.else
7.    writeToOutput("Passwords do not match");
```

It's the Data Flow!!

- Data input to a program may have security requirements
  - E.g., it is secret
- The program statements enable the data to "flow" through the program
  - Track each variable's label (based on the data it's seen)
- Enforce a data security requirements on information flows
  - Can that data be sent out to a file?
- Can connect OS/VM and program enforcement

Concepts

- Attach security labels to program data
- Enable static checking of information flows
  - Compatible with Denning's model
  - Only a program with legal information flows will compile
- Programmers can *declassify* labels
  - Upgrade integrity
  - Downgrade secrecy
- Generalize approach
  - Label polymorphism
  - Run-time label checking

Denning's Lattice Model

- Formalizes information flow models
  - FM = {N, P, SC, /, >}
- Shows that the information flow model instances form a lattice
  - N are objects, P are processes,
  - {SC, >} is a partial ordered set,
  - SC, the set of security classes is finite,
  - SC has a lower bound,
  - and / is a lub operator
- Implicit and explicit information flows
- Semantics for verifying that a configuration is secure
- Static and dynamic binding considered
- Biba and BLP are among the simplest models of this type

Implicit and explicit flows

- Explicit
  - Direct transfer to b from a (e.g., b = a)
- Implicit
  - Where value of b may depend on value of a indirectly (e.g., if a = 0, then b = c)
- Model covers all programs
  - Statement S
  - Sequence S1, S2
  - Conditional c: S1, …, Sm
- Implicit flows only occur in conditionals

Preventing Implicit Flows

PENNSTATE

- Hard to do without static analysis
- Consider code fragment

```
x := 0
if b then
    x := 1
end
```

- Assume b is more sensitive than x
- With a runtime check
  - x=1, then b is obviously leaked, but not if x=0
- Need a static analysis to detect

Static and Dynamic Binding

- Static binding
  - Security class of an object is fixed
  - This is the case for BLP and Biba
  - This is the case for most system models
- Dynamic binding
  - Security class of an object can change
  - For b = a, then the security class of b is b / a
  - E.g., High-water mark secrecy, LOMAC, IX, …

Semantics

- Program is secure if:
  - Explicit flow from S is secure
  - Explicit flow of all statements in a sequence are secure (e.g., S1; S2)
  - Conditional c: S1, …, Sm is secure if:
    - The explicit flows of all statements *S1, …, Sm* are secure
    - The implicit flows between c and the objects in Si are secure

Type Safety

- A type-safe language maintains the semantics of types. E.g. can't add int's to Object's.
- Type-safety is compositional. A function promises to maintain type safety.

<u>Example 1</u>

```
Object obj;
int i;
obj = obj + i;
```

<u>Example 2</u>

```
String proc_obj(Object o);
...
main()
{
  Object obj;
  String s = proc_obj(obj);
  ...
}
```

Security Types

Example 1

```
int{high} h1,h2;
int{low} l;
l = 5;
h2 = l;
h1 = h2 + 10;
l = h2 + l;
```

- Key insight: label types with security levels
- Security-typing is compositional

Example 2

```
String{low}
proc(Object{high} o);
...
main()
{
  Object{high} obj;
  String{low} s;
  s = proc_obj(obj);
  ...
}
```

Decentralized Label Model

- Labels have *owners* and *readers*
  - *Owner:* whose data was observed to generate value
  - *Reader:* principals allowed by an owner to read
  - Readers are specified by each owner
- Label representation
  - L = {o1: r1, r2; o2: r2, r3}
- Channel
  - Values are written to *output channels*
  - Each channel has a set of readers
- Effective Readers
  - Intersection of all reader sets of the label
  - Effective readers of L are {r2} because only it can read from o1 and o2
- Act for
  - Readers can "act for" others, using their permissions
- Semantics
  - *A value can be written to a channel only if each channel reader has authority to act for some effective reader for the value*

Example

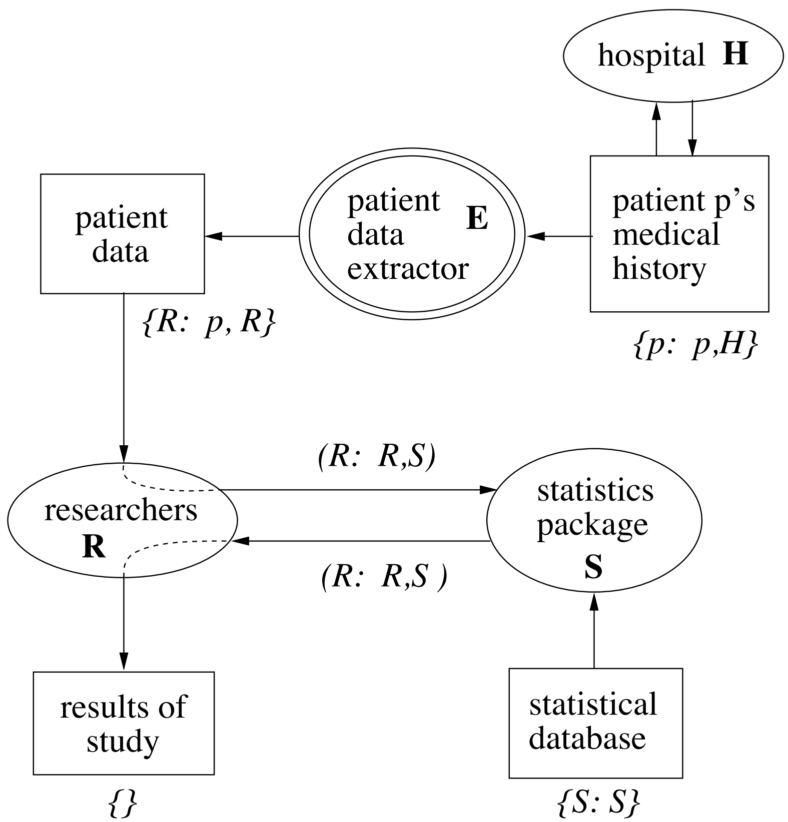


Figure 1: Medical Study Scenario

Example

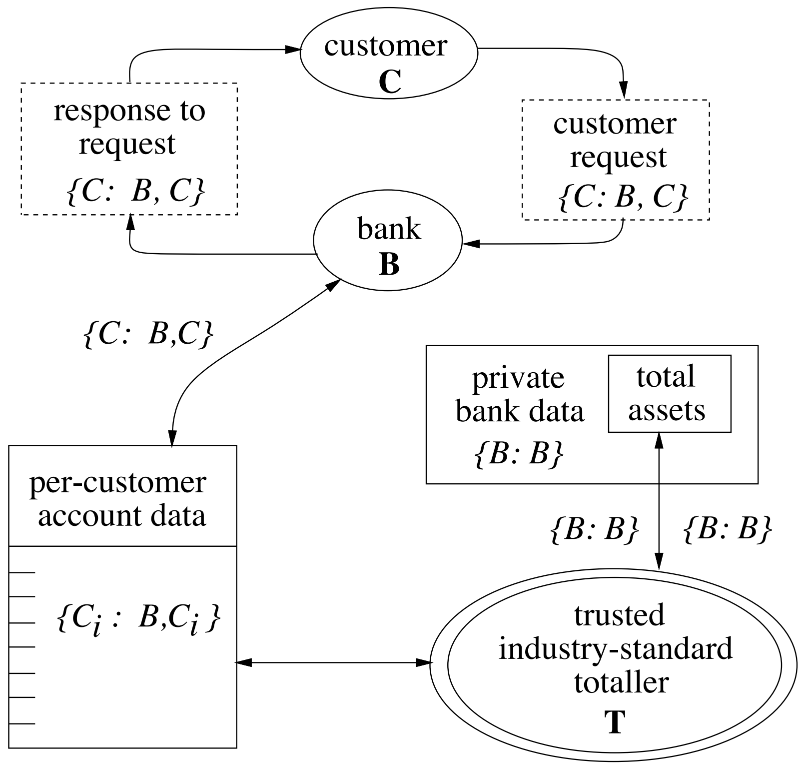


Figure 2: Bank Scenario

Relabeling Semantics

- Basics
  - Assignment causes a relabel of value
  - Default is *restriction* according to *-property
    - A new label contains the owners of the old, but same or fewer readers
- *Declassification* semantics
  - An authority for an owner can
    - Remove that owner
    - Add readers for that owner

Combination Semantics

PENNSTATE

- Join (e.g., multiply 2 numbers)
  - Assign value of label L to variable with value of label L' results in a join of L and L'
  - Least restrictive combination
  - Least upper bound
  - Union owners and intersect readers
- Meet (dual of join):
  - Most restrictive label that can apply to each input for join to be possible
  - Greatest lower bound
  - Fewest readers to achieve join label, most owners…

Label Hierarchies

- Acts-for defines a hierarchy
  - HMO acts-for A
  - B acts-for doctors
  - Secret acts-for classified
- Labels as flows -- Forms an information flow lattice
- Constraints
  - *Reader constraint*: flows contain (o, r) and r’ acts-for r, then set contains (o, r’)
  - *Owner constraint*: flows contain (o,r) and o’ acts-for o, then set contains (o’, r)
    - Or flow set does not contain (o’, r) and o’ acts-for o, then set does not contain (o, r)

Example

Hierarchy

E acts for p:

Changes owner to R

Declassify

R removes p

and adds

reader S

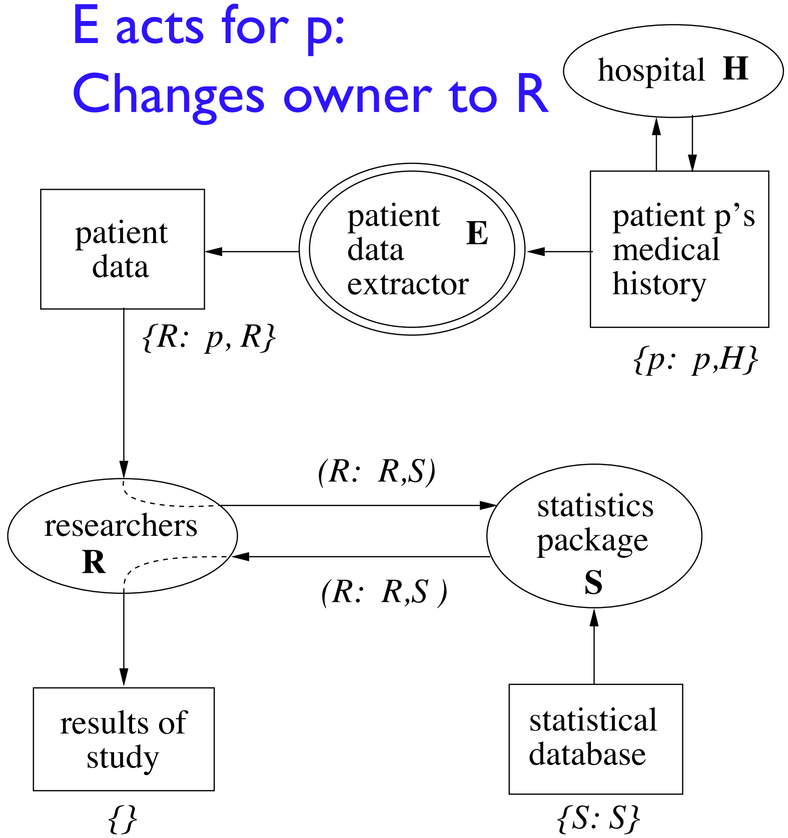


Figure 1: Medical Study Scenario

Example

Access
C controls
its own data

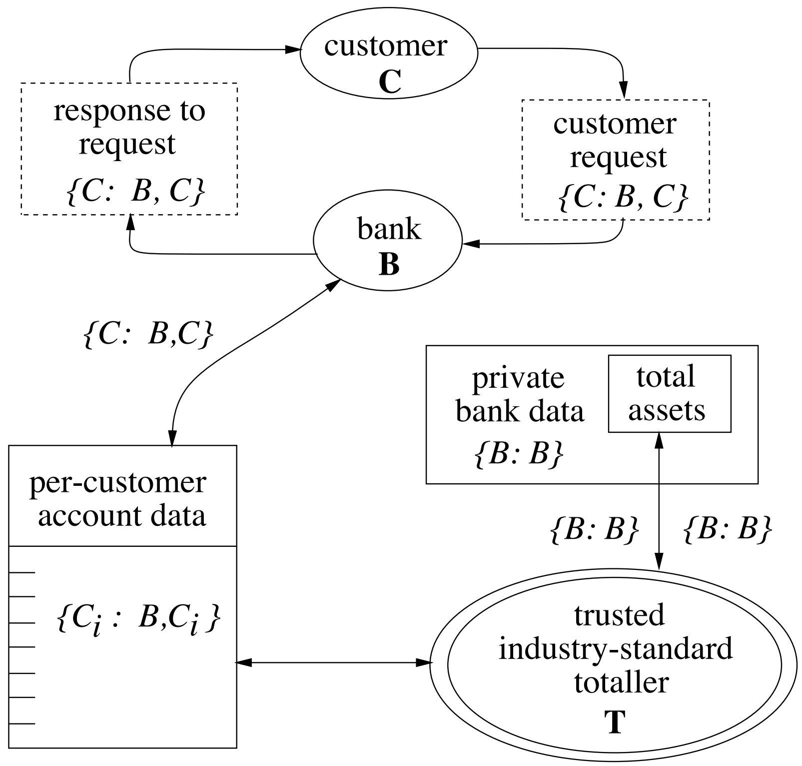


Figure 2: Bank Scenario

Hierarchy
T acts for C:
T removes Ci
from owner

Language Support

- Java Information Flow (Jif) has runtime and compilers
  - Several applications of Jif have been developed
- Challenge: labeling and error resolution
  - How do you annotate data with security?
  - How do you fix errors?
    - Many occur due to implicit flows
- Research in automatic retrofitting of programs with security type annotations and mediation

Take Away

- Programs may have the authority to protect security-sensitive data
  - OS may allow them to access data with multiple security requirements
- Program data flows for the basis for reasoning about how program authority is used
  - Can secrets flow to public objects? Can untrusted data flow to trusted?
- Denning model defines secure information flow
- DLM model generalizes to arbitrary policies

Sound relabeling

- Based on static hierarchy (actsFor)
- Claim: cannot use static correctness
- Example:
  - L1={docs: pA; B: pA, pB}
  - L2={docs: docs, pA; B: pA, pB}
- If B => docs
  - L2={docs: pA; B: pA, pB} -- B overrules docs
- If pB => docs at runtime
  - L1={docs: pA, pB; B: pA, pB} -- pB is allowed by B
  - Inconsistent

Sound and complete relabeling

- Choices
  - A reader may be dropped from some owner's reader set
  - A new owner may be added with a reader set
  - A reader may be added when it actsFor an existing reader in reader set
  - An owner may be replaced by an owner that actsFor it
- This is all the sound relabelings
- What does this mean in the previous case?

Meet Semantics Clarified

PENNSTATE 1855

- Most restrictive label that can be relabeled to both
  - For inference
- Join of all pairwise components
  - Unrelated owners ==> { }
  - Related owners ==> o' actsFor o
    - {o: r1, r2} meet {o': r3, r4} = {o: r1, r2, r3, r4}