Information Flow

Overview

- Basics and background
- Compiler-based mechanisms
- Execution-based mechanisms

1

Basics

- Bell-LaPadula Model embodies information flow policy
  - Given labels *A*, *B*, info can flow from *A* to *B* iff *B dom A*
- Variables *x*, *y* assigned labels $\underline{x}$, $\underline{y}$ (as well as values)
  - If $\underline{x}$ = *A* and $\underline{y}$ = B, and *B dom A*, then the assignment *y* := *x* is allowed but *x* := *y* is not

2

Information Flow

- Idea: info flows from *x* to *y* as a result of a sequence of commands *c* if you can deduce **information** about *x* (as simple as excluding possible values) before *c* from the value in *y* after *c*

3

Example 1

- Command is *x* := *y* + *z*; where:
  - $0 \leq y \leq 7$, equal probability
  - $z = 1$ with prob. 1/2, $z = 2$ or 3 with prob. 1/4 each
- If you know final value of *x*, initial value of *y* can have at most 3 values, so information flows from *y* to *x*

4

Example 2

- Command is
  - `if x = 1 then y := 0 else y := 1;`

  where:
  - *x*, *y* equally likely to be either 0 or 1
- But if *x* = 1 then *y* = 0, and vice versa, so value of *y* depends on *x*
- So information flows from *x* to *y*

5

Implicit Flow of Information

- Information flows from *x* to *y* without an *explicit* assignment of the form *y* := *f*(*x*)
- Example from previous slide:
  - `if x = 1 then y := 0`
    `else y := 1;`
- So must look for implicit flows of information to analyze program

6

Notation

- $\underline{x}$ means class of x
  - In Bell-LaPadula based system, same as "label of security compartment to which x belongs"
- $\underline{x} \leq \underline{y}$ means "information can flow from an element in class of x to an element in class of y
  - Or, "information with a label placing it in class $\underline{x}$ can flow into class $\underline{y}$"

7

Compiler-Based Mechanisms

- Detect unauthorized information flows in a program during compilation
- Analysis not precise, 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 the flows in set of statements do not violate that policy

8

Example

```
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 $\underline{x} \le \underline{y}$ **and** $\underline{a} \le \underline{y}$ **and** $\underline{b} \le \underline{y}$
  - Note: flows for *both* branches must be allowed unless compiler can determine that one branch will *never* be taken

9

Declarations

- Notation:

```
x: int class { A, B }
```

  means *x* is an integer variable with security class at least *lub*{ A, B }, so *lub*{ A, B } ≤ $\underline{x}$
- Distinguished classes *Low*, *High*
  - Constants are always *Low*

10

Input Parameters

- Parameters through which data passed into procedure
- Class of parameter is class of actual argument

i_p: **type class** { i_p }

11

Output Parameters

- Parameters through which data passed out of procedure
  - If data passed in, called input/output parameter
- As information can flow from input parameters to output parameters, class must include this:

  o_p: **type class** { r_1, …, r_n }

  where r_i is class of ith input or input/output argument from which info. flows into output o_p

12

Example

```
proc sum(x: int class { A };
     var out: int class { A, B });
begin
  out := out + x;
end;
```

- Require *x* ≤ *out* and *out* ≤ *out*

13

Array Elements

- Information flowing out:

```
… := a[i]
```

  Value of i, a[i] both affect result, so class is lub{ a[i], i }
- Information flowing in:

```
a[i] := …
```

- Only value of a[i] affected, so class is a[i]

14

Assignment Statements

`x := y + z;`

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

More generally:

$y := f(x_1, \ldots, x_n)$

- Information flow from the input values to the result, so lub{ $\underline{x_1}$, …, $\underline{x_n}$ } ≤ $\underline{y}$ must hold

15

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

16

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{ $\underline{x}_1$, …, $\underline{x}_n$ } ≤
  glb{$\underline{y}$ | y target of assignment in S_1 or S_2 }

17

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;
```

- Loop must terminate;
- S must be secure
- lub{ $\underline{x}_1$, …, $\underline{x}_n$ } ≤
  glb{$\underline{y}$ | y target of assignment in S }

18

Goto Statements

- No assignments
  - Hence no explicit flows
- Need to detect implicit flows
- *Basic block* is a sequence of statements that have one entry point and one exit point
  - Control in block *always* flows from entry point to exit point

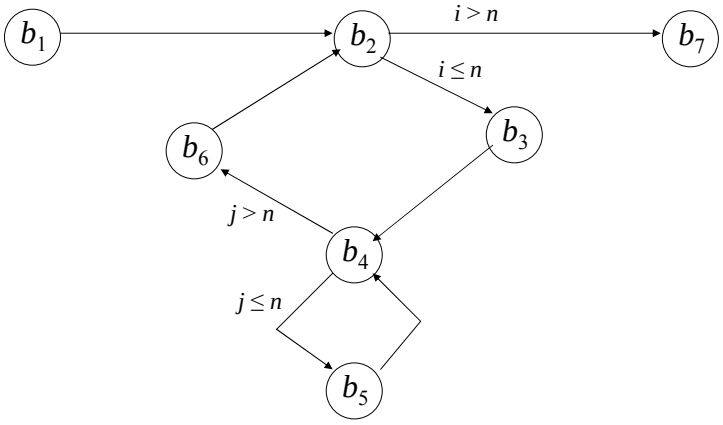
19

Example Program

```
proc tm(x: array[1..10][1..10] of int class {x};
    var y: array[1..10][1..10] of int class {y});
var i, j: int class {i};
begin
b1      i := 1;
b2  L2:   if i > 10 goto L7;
b3      j := 1;
b4  L4:   if j > 10 then goto L6;
b5    y[j][i] := x[i][j]; j := j + 1; goto L4;
b6  L6:   i := i + 1; goto L2;
b7  L7:
end;
```

20

Flow of Control



21

IFDs

- Idea: when two paths out of basic block, implicit flow occurs
  - Because information says *which* path to take
- When paths converge, either:
  - Implicit flow becomes irrelevant; or
  - Implicit flow becomes explicit
- *Immediate forward dominator* of basic block *b* (written IFD(*b*)) is the first basic block lying on all paths of execution passing through *b*

22

IFD Example

- In previous procedure:
  - IFD(b_1) = b_2 one path
  - IFD(b_2) = b_7 $b_2 \rightarrow b_7$ or $b_2 \rightarrow b_3 \rightarrow b_6 \rightarrow b_2 \rightarrow b_7$
  - IFD(b_3) = b_4 one path
  - IFD(b_4) = b_6 $b_4 \rightarrow b_6$ or $b_4 \rightarrow b_5 \rightarrow b_6$
  - IFD(b_5) = b_4 one path
  - IFD(b_6) = b_2 one path

23

Requirements

- B_i is the set of basic blocks along an execution path from b_i to IFD(b_i)
  - Analogous to statements in conditional statement
- x_{i1}, …, x_{in} variables in expression selecting which execution path containing basic blocks in B_i used
  - Analogous to conditional expression
- Requirements for secure:
  - All statements in each basic blocks are secure
  - lub{ $\underline{x}_{i1}$, …, $\underline{x}_{in}$} ≤ glb{ $\underline{y}$ | y target of assignment in B_i }

24

Example of Requirements

- Within each basic block:
  b_1: $Low \le \underline{i}$ b_3: $Low \le \underline{j}$ b_6: lub{ Low, $\underline{i}$ } $\le \underline{i}$
  b_5: lub{ $\underline{x[i][j]}$, $\underline{i}$, $\underline{j}$ } $\le \underline{y[j][i]}$; lub{ Low, $\underline{j}$ } $\le \underline{j}$
  - Combining, lub{ $\underline{x[i][j]}$, $\underline{i}$, $\underline{j}$ } $\le \underline{y[j][i]}$
  - From declarations, true when lub{ $\underline{x}$, $\underline{i}$ } $\le \underline{y}$
- $B_2 = \{b_3, b_4, b_5, b_6\}$
  - Assignments to i, j, $y[j][i]$; conditional is $i \le 10$
  - Requires $\underline{i} \le$ glb{ $\underline{i}$, $\underline{j}$, $\underline{y[j][i]}$ }
  - From declarations, true when $\underline{i} \le \underline{y}$

25

Example (continued)

- $B_4 = \{ b_5 \}$
  - Assignments to j, $y[j][i]$; conditional is $j \le 10$
  - Requires $\underline{j} \le$ glb{ $\underline{j}$, $\underline{y[j][i]}$ }
  - From declarations, means $\underline{i} \le \underline{y}$
- Result:
  - Combine lub{ $\underline{x}$, $\underline{i}$ } $\le \underline{y}$; $\underline{i} \le \underline{y}$; $\underline{i} \le \underline{y}$
  - Requirement is lub{ $\underline{x}$, $\underline{i}$ } $\le \underline{y}$

26

Procedure Calls

`tm(a, b);`

From previous slides, to be secure, lub{ $\underline{x}$, $\underline{i}$ } ≤ $\underline{y}$ must hold

- In call, *x* corresponds to *a*, *y* to *b*
- Means that lub{ $\underline{a}$, $\underline{i}$ } ≤ $\underline{b}$, or $\underline{a} \leq \underline{b}$

More generally:

`proc pn(`i_1`, …, `i_m`: int; var `o_1`, …, `o_n`: int)`
`begin S end;`

- *S* must be secure
- For all *j* and *k*, if $\underline{i_j} \leq \underline{o_k}$, then $\underline{x_j} \leq \underline{y_k}$
- For all *j* and *k*, if $\underline{o_j} \leq \underline{o_k}$, then $\underline{y_j} \leq \underline{y_k}$

27

Soundness

- Above exposition intuitive
- Can be (has been 1996) made rigorous:
  - Express flows as types
  - Equate certification to correct use of types
  - Checking for valid information flows same as checking types conform to semantics imposed by security policy

28

Execution-Based Mechanisms

- Detect and stop flows of information that violate policy
  - Done at run time, not compile time
- Obvious approach: check explicit flows
  - Problem: assume for security, $\underline{x} \leq \underline{y}$

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

  - When $x \neq 1$, $\underline{x}$ = High, $\underline{y}$ = Low, $\underline{a}$ = Low, appears okay—but implicit flow violates condition!

29

Key Points

- Both amount of information, direction of flow important
  - Flows can be explicit or implicit
- Compiler-based checks flows at compile time
- Execution-based checks flows at run time

30