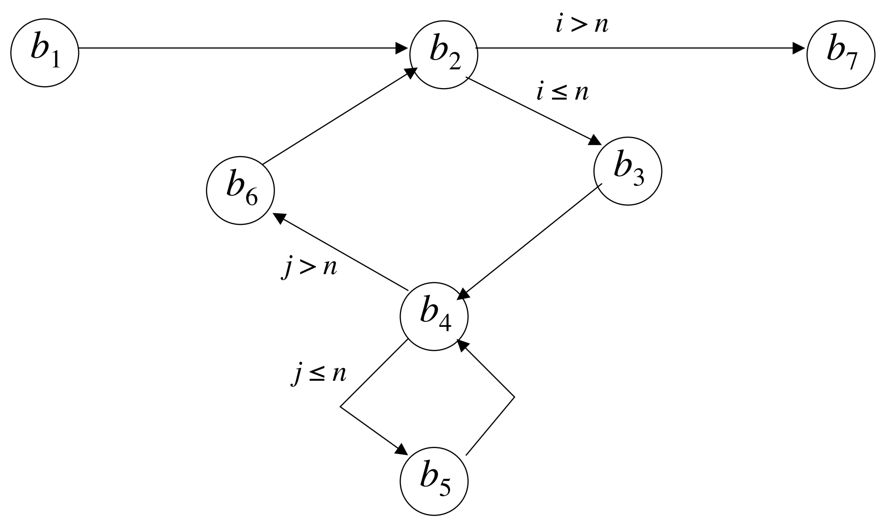
ECS 289M Lecture 18

May 12, 2006

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 {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;
```

Flow of Control



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

Example of Requirements

- Within each basic block:

  b_1: *Low* $\le \underline{i}$ $\quad$ b_3: *Low* $\le \underline{j}$ $\quad$ 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 $\underline{i} \le \underline{y}$

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{ $\underline{x}$, $\underline{i}$ } $\le \underline{y}$

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 $\underline{a} \le \underline{b}$

More generally:

```
proc pn(i1, …, im: int; var o1, …, on: int)
begin S end;
```

- *S* must be secure
- For all *j* and *k*, if $\underline{i}_j \le \underline{o}_k$, then $\underline{x}_j \le \underline{y}_k$
- For all *j* and *k*, if $\underline{o}_j \le \underline{o}_k$, then $\underline{y}_j \le \underline{y}_k$

Exceptions

```
proc copy(x: int class { x };
                var y: int class Low)
var sum: int class { x };
    z: int class Low;
begin
     y := z := sum := 0;
     while z = 0 do begin
          sum := sum + x;
          y := y + 1;
     end
end
```

Exceptions (*cont*)

- When sum overflows, integer overflow trap
  - Procedure exits
  - Value of *x* is MAXINT/*y*
  - Info flows from *y* to *x*, but <u>*x*</u> ≤ <u>*y*</u> never checked
- Need to handle exceptions explicitly
  - Idea: on integer overflow, terminate loop

```
on integer_overflow_exception sum do z := 1;
```

  - Now info flows from *sum* to *z*, meaning <u>*sum*</u> ≤ <u>*z*</u>
  - This is false (<u>*sum*</u> = { x } dominates <u>*z*</u> = Low)

Infinite Loops

```
proc copy(x: int 0..1 class { x };
                var y: int 0..1 class Low)
begin
     y := 0;
     while x = 0 do
          (* nothing *);
     y := 1;
end
```

- If *x* = 0 initially, infinite loop
- If *x* = 1 initially, terminates with *y* set to 1
- No explicit flows, but implicit flow from *x* to *y*

Semaphores

Use these constructs:

```
wait(x):   if x = 0 then block until x > 0; x := x – 1;
signal(x): x := x + 1;
```

– x is semaphore, a shared variable

– Both executed atomically

Consider statement

```
wait(sem); x := x + 1;
```

- Implicit flow from *sem* to *x*
  - Certification must take this into account!

Flow Requirements

- Semaphores in *signal* irrelevant
  - Don't affect information flow in that process
- Statement S is a wait
  - shared(S): set of shared variables read
    - Idea: information flows out of variables in shared(S)
  - fglb(S): glb of assignment targets *following* S
  - So, requirement is shared(S) ≤ fglb(S)
- begin S_1; … S_n end
  - All S_i must be secure
  - For all i, shared(S_i) ≤ fglb(S_i)

Example

```
begin
    x := y + z;        (* S1 *)
    wait(sem);         (* S2 *)
    a := b * c – x;    (* S3 *)
end
```

- Requirements:
  - lub{ $\underline{y}$, $\underline{z}$ } ≤ $\underline{x}$
  - lub{ $\underline{b}$, $\underline{c}$, $\underline{x}$ } ≤ $\underline{a}$
  - $\underline{sem}$ ≤ $\underline{a}$
    - Because fglb(S_2) = $\underline{a}$ and shared(S_2) = *sem*

Concurrent Loops

- Similar, but wait in loop affects *all* statements in loop
  - Because if flow of control loops, statements in loop before wait may be executed after wait
- Requirements
  - Loop terminates
  - All statements S_1, …, S_n in loop secure
  - lub{ $\underline{\text{shared}(S_1)}$, …, $\underline{\text{shared}(S_n)}$ } ≤ glb(t_1, …, t_m)
    - Where t_1, …, t_m are variables assigned to in loop

Loop Example

```
while i < n do begin
    a[i] := item;        (* S1 *)
    wait(sem);           (* S2 *)
    i := i + 1;          (* S3 *)
end
```

- Conditions for this to be secure:
  - Loop terminates, so this condition met
  - S_1 secure if lub{ $\underline{i}$, $\underline{item}$ } ≤ $\underline{a[i]}$
  - S_2 secure if $\underline{sem}$ ≤ $\underline{i}$ and $\underline{sem}$ ≤ $\underline{a[i]}$
  - S_3 trivially secure

cobegin/coend

```
cobegin
    x := y + z;          (* S1 *)
    a := b * c – y;      (* S2 *)
coend
```

- No information flow among statements
  - For S_1, lub{ $\underline{y}$, $\underline{z}$ } ≤ $\underline{x}$
  - For S_2, lub{ $\underline{b}$, $\underline{c}$, $\underline{y}$ } ≤ $\underline{a}$
- Security requirement is both must hold
  - So this is secure if lub{ $\underline{y}$, $\underline{z}$ } ≤ $\underline{x}$ ∧ lub{ $\underline{b}$, $\underline{c}$, $\underline{y}$ } ≤ $\underline{a}$

Soundness

- Above exposition intuitive
- Can be 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

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, $\underline{x} \le \underline{y}$

```
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!

Fenton's Data Mark Machine

- Each variable has an associated class
- Program counter (PC) has one too
- Idea: branches are assignments to PC, so you can treat implicit flows as explicit flows
- Stack-based machine, so everything done in terms of pushing onto and popping from a program stack

Instruction Description

- *skip* means instruction not executed
- *push*(x, $\underline{x}$) means push variable x and its security class $\underline{x}$ onto program stack
- *pop*(x, $\underline{x}$) means pop top value and security class from program stack, assign them to variable x and its security class $\underline{x}$ respectively

Instructions

- x := x + 1 (increment)
  - Same as:

    if $\underline{PC} \le \underline{x}$ then x := x + 1 else *skip*
- if x = 0 then goto n else x := x – 1 (branch and save PC on stack)
  - Same as:

```
if x = 0 then begin
 push(PC, PC); PC := lub{PC, x}; PC := n;
end else if PC ≤ x then
 x := x - 1
else
 skip;
```


More Instructions

- if′ x = 0 then goto n else x := x – 1 (branch without saving PC on stack)
  - Same as:

```
if x = 0 then
 if x ≤ PC then PC := n else skip
else
 if PC ≤ x then x := x - 1 else skip
```

More Instructions

- `return` (go to just after last *if*)
  - Same as:

    `pop(`*PC*`, `<u>*PC*</u>`);`
- `halt` (stop)
  - Same as:

    `if` *program stack empty* `then` *halt*
  - Note stack empty to prevent user obtaining information from it after halting

Example Program

```
1    if x = 0 then goto 4 else x := x - 1
2    if z = 0 then goto 6 else z := z - 1
3    halt
4    z := z - 1
5    return
6    y := y - 1
7    return
```

- Initially $x = 0$ or $x = 1$, $y = 0$, $z = 0$
- Program copies value of x to y

Example Execution

x	*y*	*z*	*PC*	*<u>PC</u>*	*stack*	*check*
1	0	0	1	Low	—	
0	0	0	2	Low	—	Low ≤ $\underline{x}$
0	0	0	6	$\underline{z}$	(3, Low)	
0	1	0	7	$\underline{z}$	(3, Low)	$\underline{PC}$ ≤ $\underline{y}$
0	1	0	3	Low	—	

Handling Errors

- Ignore statement that causes error, but continue execution
  - If aborted or a visible exception taken, user could deduce information
  - Means errors cannot be reported unless user has clearance at least equal to that of the information causing the error

Variable Classes

- Up to now, classes fixed
  - Check relationships on assignment, etc.
- Consider variable classes
  - Fenton's Data Mark Machine does this for <u>*PC*</u>
  - On assignment of form $y := f(x_1, \ldots, x_n)$, $\underline{y}$ changed to lub{ $\underline{x}_1, \ldots, \underline{x}_n$ }
  - Need to consider implicit flows, also

Example Program

```
(* Copy value from x to y
 * Initially, x is 0 or 1 *)
proc copy(x: int class { x };
                  var y: int class { y })
var z: int class variable { Low };
begin
  y := 0;
  z := 0;
  if x = 0 then z := 1;
  if z = 0 then y := 1;
end;
```

- $\underline{z}$ changes when z assigned to
- Assume $\underline{y} < \underline{x}$

Analysis of Example

- $x = 0$
  - `z := 0` sets $\underline{z}$ to Low
  - `if x = 0 then z := 1` sets z to 1 and $\underline{z}$ to $\underline{x}$
  - So on exit, $y = 0$
- $x = 1$
  - `z := 0` sets $\underline{z}$ to Low
  - `if z = 0 then y := 1` sets y to 1 and checks that lub{Low, $\underline{z}$} ≤ $\underline{y}$
  - So on exit, $y = 1$
- Information flowed from $\underline{x}$ to $\underline{y}$ even though $\underline{y} < \underline{x}$

Handling This (1)

- Fenton's Data Mark Machine detects implicit flows violating certification rules