May 12: Information Flow

- Static (compile-time) mechanisms
- Dynamic (run-time) mechanisms

Array Elements

- Information flowing out:

  `... := a[i]`

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

  `a[i] := ...`
- Only value of $a[i]$ affected, so class is $\underline{a[i]}$

Assignment Statements

`x := y + z;`

- Information flows from *y*, *z* to *x*, so this requires $lub(\underline{y}, \underline{z}) \leq \underline{x}$

More generally:

$$\texttt{y := f(}x_1\texttt{, ..., }x_n\texttt{)}$$

- the relation $lub(\ \underline{x}_1, \ldots, x_n) \leq \underline{y}$ must hold

Compound Statements

```
x := y + z; a := b * c – x;
```

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

More generally:

$$S_1;\ \ldots;\ S_n;$$

- Each individual S_i must be secure

Conditional Statements

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

- 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(x1, ..., xn) then S1 else S2; end
```

- S_1, S_2 must be secure
- $lub(\underline{x}_1, \ldots, \underline{x}_n) \leq$

  $glb(\underline{y} \mid y \text{ target of assignment in } S_1, S_2)$

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($x_1$, ..., $x_n$) do S;
```

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

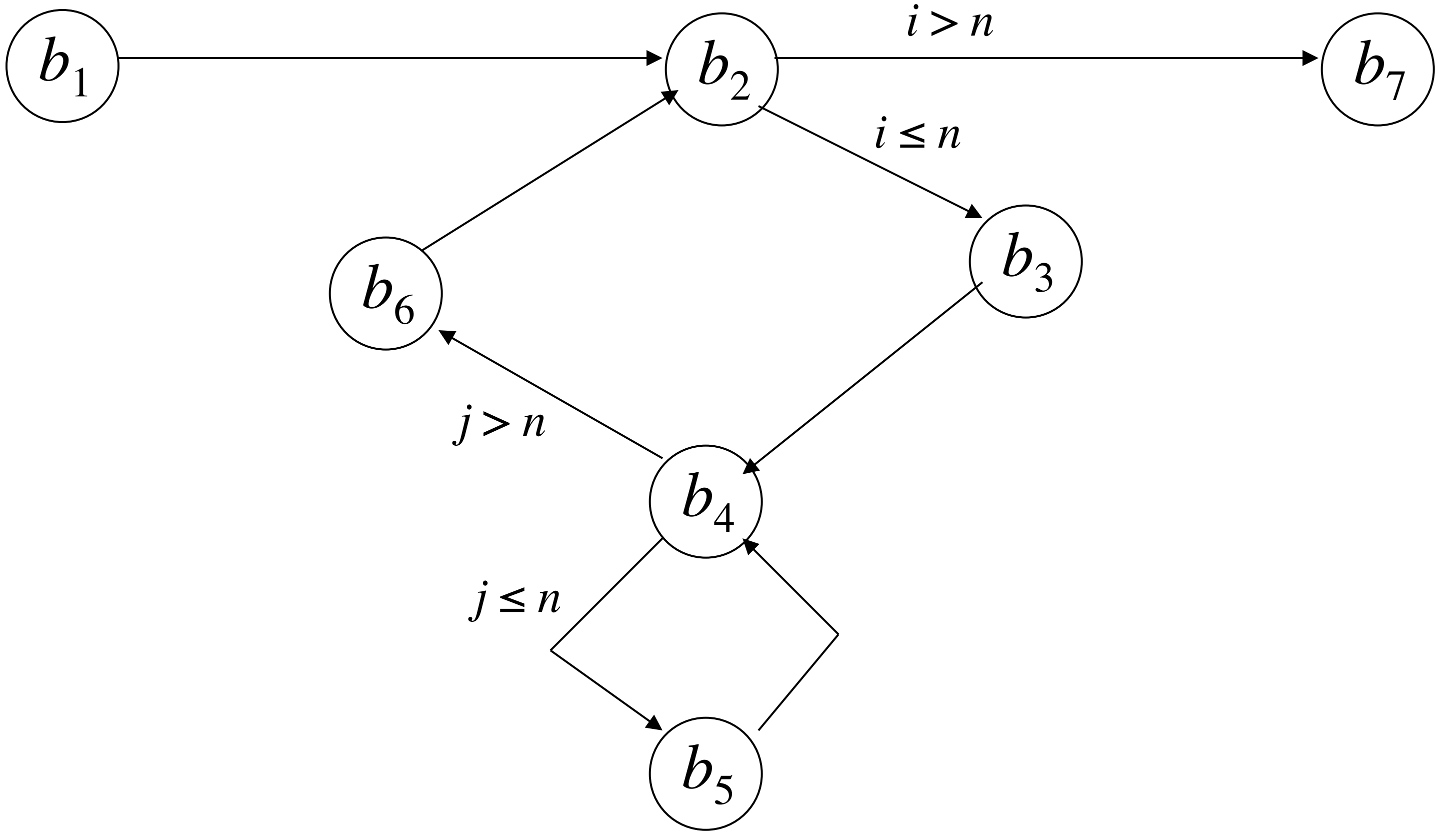
Goto Statements

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

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 then 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



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 a basic block *b* (written IFD(*b*)) is the first basic block lying on all paths of execution passing through *b*

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

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
- $x_{i1}, \ldots, x_{in}$ variables in expression selecting which execution path containing basic blocks in B_i used
  - Analogous to conditional expression
- Requirements for being secure:
  - All statements in each basic blocks are secure
  - $lub(\underline{x}_{i1}, \ldots, \underline{x}_{in}) \leq glb\{\ \underline{y} \mid y$ target of assignment in $B_i\ \}$

Example of Requirements

- Within each basic block:

  b_1: $Low \le \underline{i}$ b_3: $Low \le \underline{j}$ b_6: $\text{lub}\{ Low, \underline{i} \} \le \underline{i}$

  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, $lub(\underline{x}, \underline{i}) \leq \underline{y}$ must hold

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

More generally:

`proc` $pn(i_1, \ldots, i_m$`: int; var` $o_1, \ldots, o_n$`: 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 $\underline{y_j} \leq \underline{y_k}$

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 $\underline{x} \le \underline{y}$ 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 $\underline{sum} \le \underline{z}$
  - This is false ($\underline{sum}$ = { *x* } dominates $\underline{z}$ = 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 $\underline{\textit{shared}(S)} \le \textit{fglb}(S)$
- begin S_1; . . . S_n end
  - All S_i must be secure
  - For all i, $\underline{\textit{shared}(S_i)} \le \textit{fglb}(S_i)$

Example

```
begin
    x := y + z;          (* $S_1$ *)
    wait(sem);           (* $S_2$ *)
    a := b * c – x;      (* $S_3$ *)
end
```

- Requirements:
  - $lub(\underline{y}, \underline{z}) \le \underline{x}$
  - $lub(\underline{b}, \underline{c}, \underline{x}) \le \underline{a}$
  - $\underline{sem} \le \underline{a}$
    - 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 $S_1, \ldots, S_n$ in loop secure
  - $lub(\underline{shared(S_1)}, \ldots, \underline{shared(S_n)}\ \} \leq glb(t_1, \ldots, t_m)$
    - Where $t_1, \ldots, t_m$ are variables assigned to in loop

Loop Example

```
while $i$ < $n$ do begin
    $a[i]$ := $item$;       (* $S_1$ *)
    wait($sem$);            (* $S_2$ *)
    $i$ := $i$ + 1;         (* $S_3$ *)
end
```

- Conditions for this to be secure:
  - Loop terminates, so this condition met
  - S_1 secure if $lub(\underline{i}, \underline{item}) \leq \underline{a[i]}$
  - S_2 secure if $\underline{sem} \leq \underline{i}$ and $\underline{sem} \leq \underline{a[i]}$
  - 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, $lub(\underline{y}, \underline{z}) \leq \underline{x}$
  - For S_2, $lub(\underline{b}, \underline{c}, \underline{y}) \leq \underline{a}$
- Security requirement is both must hold
  - So this is secure if $lub(\underline{y}, \underline{z}) \leq \underline{x} \wedge lub(\underline{b}, \underline{c}, \underline{y}) \leq \underline{a}$

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, $\underline{PC}$); $\underline{PC}$ := lub{$\underline{PC}$, x}; PC := n;
    end else if $\underline{PC} \le \underline{x}$ 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 $\underline{x} \le \underline{PC}$ then $PC$ := $n$ else skip
else
  if $\underline{PC} \le \underline{x}$ then $x$ := $x$ - 1 else skip
```

More Instructions

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

    `pop(PC, PC);`
- `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	$\underline{PC}$	*stack*	*check*
1	0	0	1	Low	—	
0	0	0	2	Low	—	Low $\leq \underline{x}$
0	0	0	6	$\underline{z}$	(3, Low)	
0	1	0	7	$\underline{z}$	(3, Low)	$\underline{PC} \leq \underline{y}$
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 $\underline{PC}$
  - 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, $\underline{z}$} $\leq \underline{y}$
  - 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

Handling This (2)

- Raise class of variables assigned to in conditionals even when branch not taken
- Also, verify information flow requirements even when branch not taken
- Example:
  - In `if x = 0 then z := 1`, z raised to x whether or not $x = 0$
  - Certification check in next statement, that $\underline{z} \leq \underline{y}$, fails, as $\underline{z} = \underline{x}$ from previous statement, and $\underline{y} \leq \underline{x}$

Handling This (3)

- Change classes only when explicit flows occur, but *all* flows (implicit as well as explicit) force certification checks
- Example
  - When $x = 0$, first “if” sets $\underline{z}$ to Low then checks $\underline{x} \le \underline{z}$
  - When x = 1, first “if” checks that $\underline{x} \le \underline{z}$
  - This holds if and only if $\underline{x}$ = Low
    - Not possible as $\underline{y} < \underline{x}$ = Low and there is no such class