ECS 235B Module 45
Compiler Based
Information Flow Mechanisms

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 flows in set of statements do not violate that policy

Example

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

- Information 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 true unless compiler can determine that one branch will *never* be taken

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*

Input Parameters

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

$$i_p\textbf{: } \textbf{\textit{type}} \textbf{ class } \{ \, \mathrm{i}_{\mathrm{p}} \, \}$$

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:

$$o_p\textbf{: }\boldsymbol{type}\textbf{ class }\{\ r_1,\ \ldots,\ r_n\ \}$$

where r_i is class of *i*th input or input/output argument

Example

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

- Require <u>*x*</u> ≤ <u>*out*</u> and <u>*out*</u> ≤ <u>*out*</u>

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{ $\underline{y}$, $\underline{z}$ } ≤ $\underline{x}$

More generally:

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

- the relation lub{ $\underline{x}_1$, …, x_n } ≤ $\underline{y}$ must hold

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

Conditional Statements

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

- Statement executed reveals information about *x*, *y*, *z*, so lub{ $\underline{x}$, $\underline{y}$, $\underline{z}$ } ≤ glb{ $\underline{a}$, $\underline{d}$ }

More generally:

`if` $f(x_1, \ldots, x_n)$ `then` S_1 `else` S_2`; 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, 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` $f(x_1, \ldots, x_n)$ `do` S`;`

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

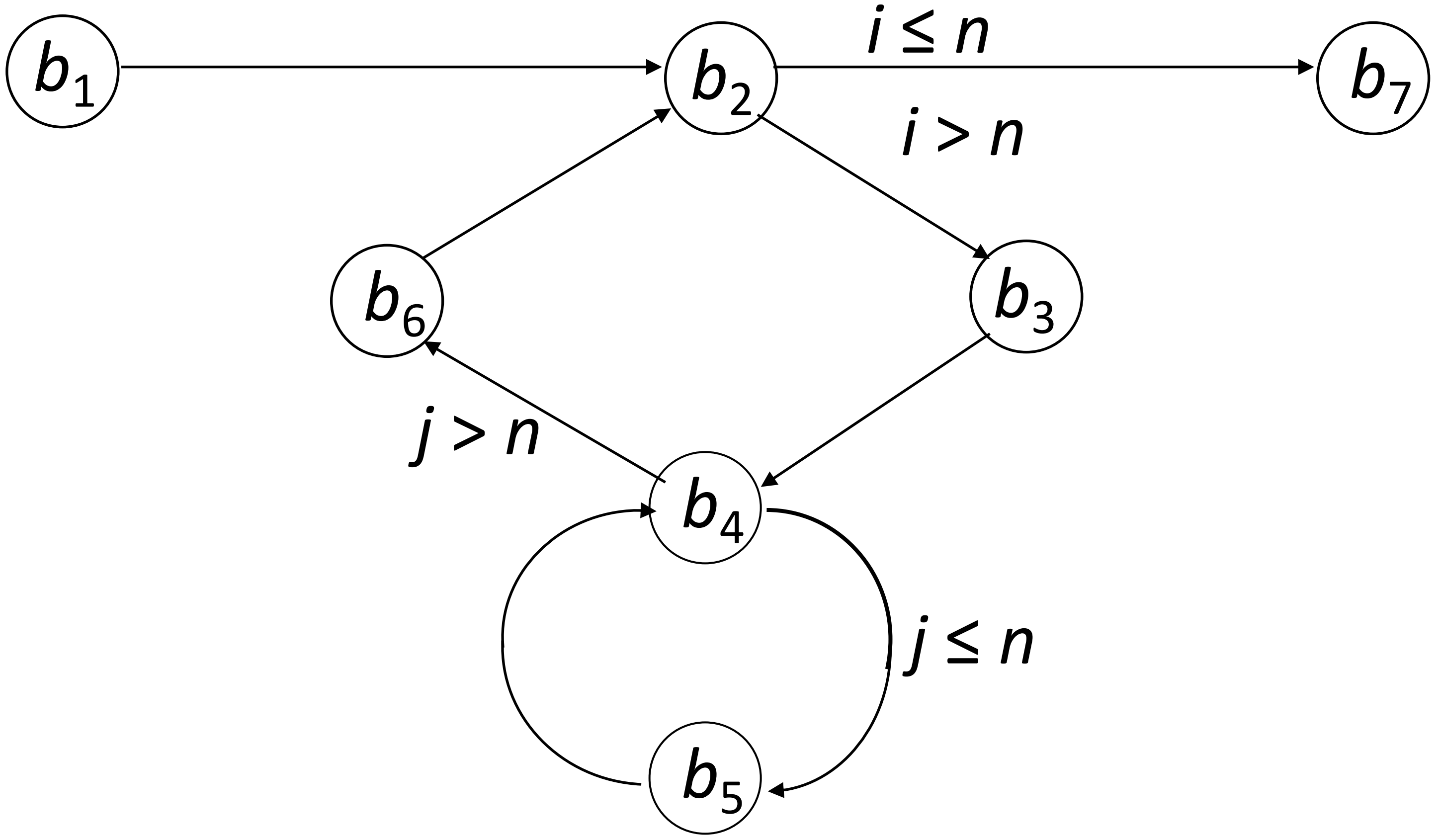
Goto Statements

- 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 integer class {x};
                  var y: array[1..10][1..10] of integer class {y});
var i, j: integer 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;
```

Flow of Control



Immediate Forward Dominators

- 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 first basic block lying on all paths of execution passing through *b*

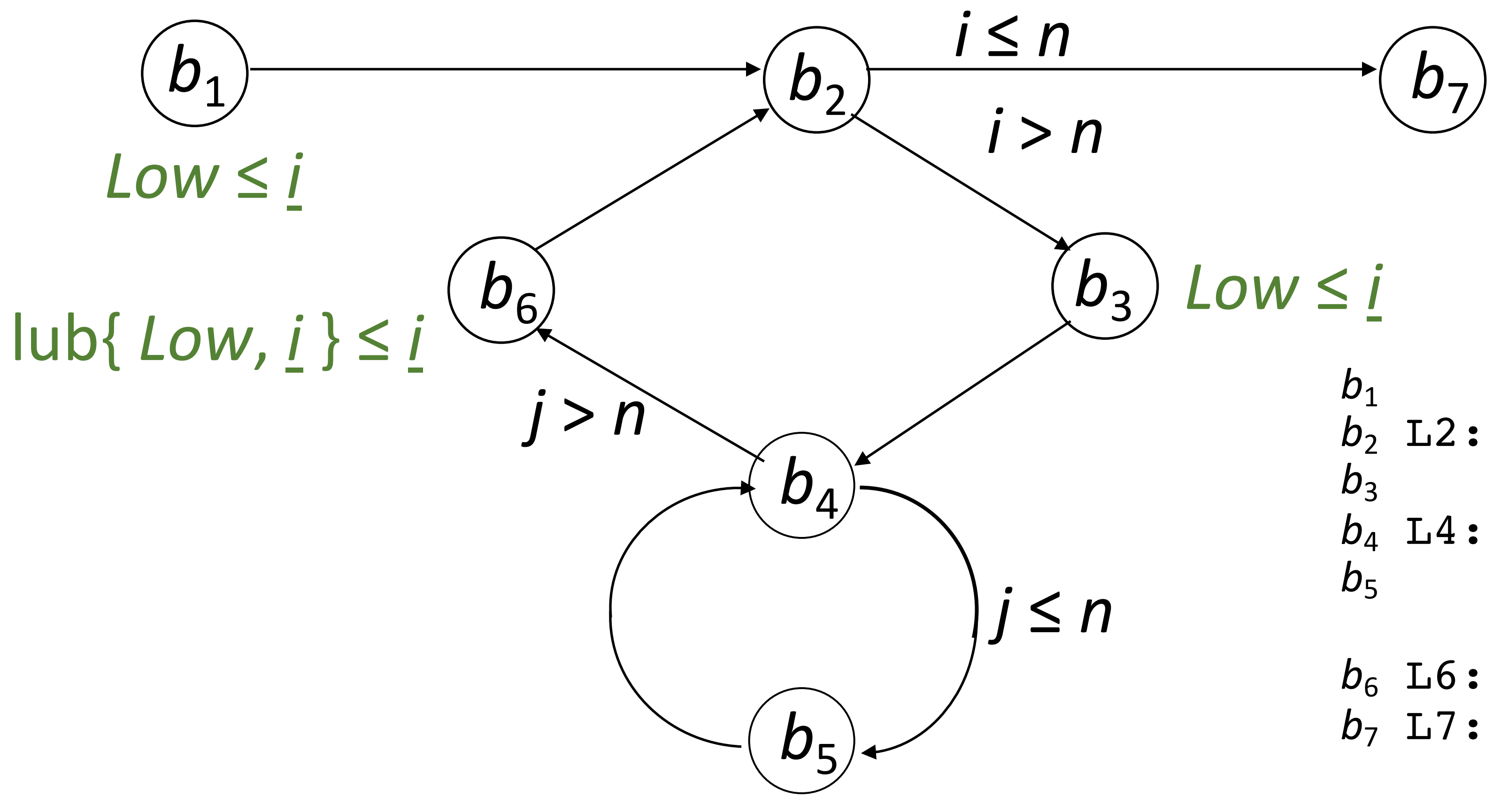
IFD Example

- 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 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 secure:
  - All statements in each basic blocks are secure
  - lub{ $\underline{x}_{i1}, \ldots, \underline{x}_{in}$ } ≤ glb{ $\underline{y}$ | y target of assignment in B_i }

Example of Requirements



lub{ x[i][j], i, j } ≤ y[j][i] }; lub{ Low, j } ≤ j

```
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:
```

Example of Requirements

- Within each basic block:

  b_1: *Low* ≤ $\underline{i}$ b_3: *Low* ≤ $\underline{j}$ b_6: lub{ *Low*, $\underline{i}$ } ≤ $\underline{i}$

  b_5: lub{ $\underline{x[i][j]}$, $\underline{i}$, $\underline{j}$ } ≤ $\underline{y[j][i]}$ }; lub{ *Low*, $\underline{j}$ } ≤ $\underline{j}$

  - Combining, lub{ $\underline{x[i][j]}$, $\underline{i}$, $\underline{j}$ } ≤ $\underline{y[j][i]}$ }
  - From declarations, true when lub{ $\underline{x}$, $\underline{i}$ } ≤ $\underline{y}$
- $B_2 = \{b_3, b_4, b_5, b_6\}$
  - Assignments to *i*, *j*, *y*[*j*][*i*]; conditional is *i* ≤ 10
  - Requires $\underline{i}$ ≤ glb{ $\underline{i}$, $\underline{j}$, $\underline{y[j][i]}$ }
  - From declarations, true when $\underline{i}$ ≤ $\underline{y}$

Example (continued)

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

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*(i_1, …, i_m: **int**; **var** o_1, …, o_n: **int**); **begin** *S* **end**;

- *S* must be secure
- For all *j* and *k*, if $\underline{i}_j \le \underline{o}_k$, 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: integer class { x };
                    var y: integer class Low);
var sum: integer 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 *sum* is MAXINT/*y*
  - Information flows from *y* to *sum*, but $\underline{sum} \le \underline{y}$ never checked
- Need to handle exceptions explicitly
  - Idea: on integer overflow, terminate loop

    on integer_overflow_exception *sum* **do** *z* := 1;
  - Now information 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: integer 0..1 class { x };
                var y: integer 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 $\underline{\text{shared}(S)} \le \text{fglb}(S)$
- begin S_1; … S_n end
  - All S_i must be secure
  - For all *i*, $\underline{\text{shared}(S_i)} \le \text{fglb}(S_i)$

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{ $\underline{y}$, $\underline{z}$ } $\leq \underline{x}$
  - 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

Quiz

In the certification of iterative statements such as a while statement, why is the condition that the loop terminate necessary?

1. If it were not present, the certification mechanism could not determine if the program will halt
2. If it were not present, then whether the loop terminates or not will cause an unauthorized leak of information
3. If it were not present, the certification mechanism could not use the requirements for the conditional (if) statement
4. It is not necessary