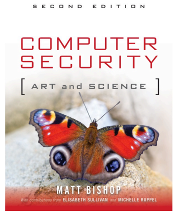
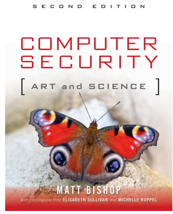


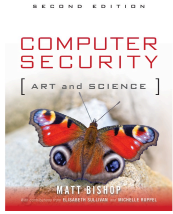
Information Flow

Chapter 17



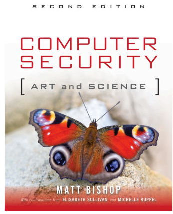
Overview

- Basics and background
  - Entropy
- Non-lattice flow policies
- Compiler-based mechanisms
- Execution-based mechanisms
- Examples
  - Privacy and cell phones
  - Firewalls



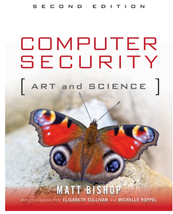
Basics

- Bell-LaPadula Model embodies information flow policy
  - Given compartments A, B, info can flow from A to B iff B *dom* A
- So does Biba Model
  - Given compartments A, B, info can flow from A to B iff A *dom* B
- Variables x, y assigned compartments $\underline{x}$, $\underline{y}$ as well as values
  - Confidentiality (Bel-LaPadula): if $\underline{x} = A$, $\underline{y} = \mathrm{B}$, and B *dom* A, then $y := x$ allowed but not $x := y$
  - Integrity (Biba): if $\underline{x} = A$, $\underline{y} = \mathrm{B}$, and A *dom* B, then $x := y$ allowed but not $y := x$
- From here on, the focus is on confidentiality (Bell-LaPadula)
  - Discuss integrity later



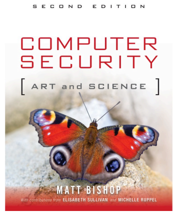
Entropy and Information Flow

- Idea: info flows from *x* to *y* as a result of a sequence of commands *c* if you can deduce information about *x* before *c* from the value in *y* after *c*
- Formally:
  - *s* time before execution of *c*, *t* time after
  - $H(x_s \mid y_t) < H(x_s \mid y_s)$
  - If no *y* at time *s*, then $H(x_s \mid y_t) < H(x_s)$



Example 1

- Command is $x := y + z$; where:
  - $0 \le y \le 7$, equal probability
  - $z = 1$ with prob. 1/2, $z = 2$ or 3 with prob. 1/4 each
- s state before command executed; t, after; so
  - $H(y_s) = H(y_t) = -8(1/8) \lg (1/8) = 3$
  - $H(z_s) = H(z_t) = -(1/2) \lg (1/2) -2(1/4) \lg (1/4) = 1.5$
- If you know x_t, y_s can have at most 3 values, so $H(y_s \mid x_t) = -3(1/3) \lg (1/3) = \lg 3 \approx 1.58$
  - Thus, information flows from y to x

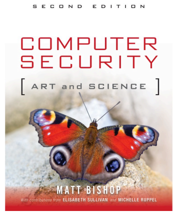


Example 2

- Command is

  if $x = 1$ **then** $y := 0$ **else** $y := 1$;

  where x, y equally likely to be either 0 or 1
- $H(x_s) = 1$ as x can be either 0 or 1 with equal probability
- $H(x_s \mid y_t) = 0$ as if $y_t = 1$ then $x_s = 0$ and vice versa
  - Thus, $H(x_s \mid y_t) = 0 < 1 = H(x_s)$
- So information flowed from x to y

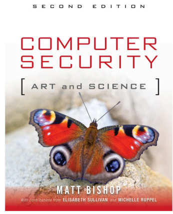


Implicit Flow of Information

- Information flows from x to y without an *explicit* assignment of the form $y := f(x)$
  - $f(x)$ an arithmetic expression with variable x
- Example from previous slide:

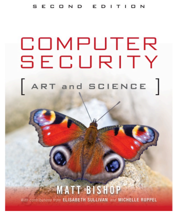
if $x = 1$ **then** $y := 0$ **else** $y := 1$;

- So must look for implicit flows of information to analyze program



Notation

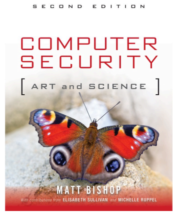
- $\underline{x}$ means class of *x*
  - In Bell-LaPadula based system, same as “label of security compartment to which *x* belongs”
- $\underline{x} \le \underline{y}$ means “information can flow from an element in class of *x* to an element in class of *y*
  - Or, “information with a label placing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



Information Flow Policies

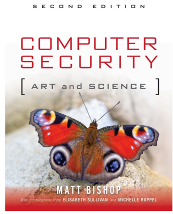
Information flow policies are usually:

- reflexive
  - So information can flow freely among members of a single class
- transitive
  - So if information can flow from class 1 to class 2, and from class 2 to class 3, then information can flow from class 1 to class 3



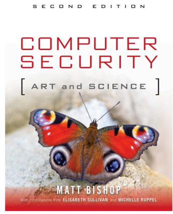
Non-Transitive Policies

- Betty is a confident of Anne
- Cathy is a confident of Betty
    - With transitivity, information flows from Anne to Betty to Cathy
- Anne confides to Betty she is having an affair with Cathy's spouse
    - Transitivity undesirable in this case, probably



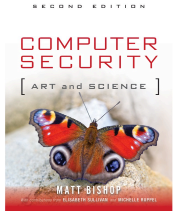
Non-Lattice Transitive Policies

- 2 faculty members co-PIs on a grant
  - Equal authority; neither can overrule the other
- Grad students report to faculty members
- Undergrads report to grad students
- Information flow relation is:
  - Reflexive and transitive
- But some elements (people) have no “least upper bound” element
  - What is it for the faculty members?



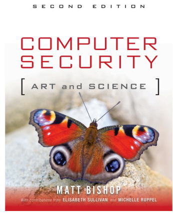
Confidentiality Policy Model

- Lattice model fails in previous 2 cases
- Generalize: policy $I = (SC_I, \le_I, join_I)$:
  - SC_I set of security classes
  - $\le_I$ ordering relation on elements of SC_I
  - $join_I$ function to combine two elements of SC_I
- Example: Bell-LaPadula Model
  - SC_I set of security compartments
  - $\le_I$ ordering relation *dom*
  - $join_I$ function *lub*



Confinement Flow Model

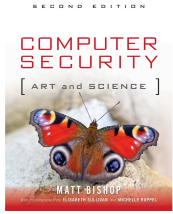
- $(I, O, \mathit{confine}, \rightarrow)$
    - $I = (SC_I, \leq_I, \mathit{join}_I)$
    - O set of entities
    - $\rightarrow$: $O \times O$ with $(a, b) \in \rightarrow$ (written $a \rightarrow b$) iff information can flow from a to b
    - for $a \in O$, $\mathit{confine}(a) = (a_L, a_U) \in SC_I \times SC_I$ with $a_L \leq_I a_U$
        - Interpretation: for $a \in O$, if $x \leq_I a_U$, information can flow from x to a, and if $a_L \leq_I x$, information can flow from a to x
        - So a_L lowest classification of information allowed to flow out of a, and a_U highest classification of information allowed to flow into a



Assumptions, *etc*.

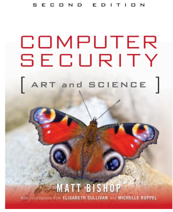
- Assumes: object can change security classes
  - So, variable can take on security class of its data
- Object x has security class $\underline{x}$ currently
- Note transitivity *not* required
- If information can flow from a to b, then b dominates a under ordering of policy I:

$$(\forall\ a, b \in O)[\ a \rightarrow b \Rightarrow a_L \leq_I b_U\ ]$$



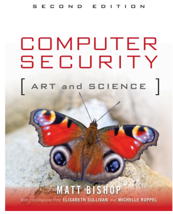
Example 1

- $SC_I = \{ U, C, S, TS \}$, with $U \leq_I C$, $C \leq_I S$, and $S \leq_I TS$
- $a, b, c \in O$
  - confine(a) = [C, C]
  - confine(b) = [S, S]
  - confine(c) = [TS, TS]
- Secure information flows: $a \rightarrow b$, $a \rightarrow c$, $b \rightarrow c$
  - As $a_L \leq_I b_U$, $a_L \leq_I c_U$, $b_L \leq_I c_U$
  - Transitivity holds



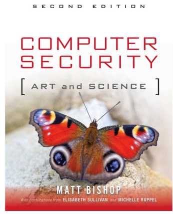
Example 2

- SC_I, $\leq_I$ as in Example 1
- $x, y, z \in O$
  - confine(x) = [C, C]
  - confine(y) = [S, S]
  - confine(z) = [C, TS]
- Secure information flows: $x \rightarrow y$, $x \rightarrow z$, $y \rightarrow z$, $z \rightarrow x$, $z \rightarrow y$
  - As $x_L \leq_I y_U$, $x_L \leq_I z_U$, $y_L \leq_I z_U$, $z_L \leq_I x_U$, $z_L \leq_I y_U$
  - Transitivity does not hold
    - $y \rightarrow z$ and $z \rightarrow x$, but $y \rightarrow z$ is false, because $y_L \leq_I x_U$ is false



Transitive Non-Lattice Policies

- Q = (S_Q, $\leq_Q$) is a *quasi-ordered set* when $\leq_Q$ is transitive and reflexive over S_Q
- How to handle information flow?
    - Define a partially ordered set containing quasi-ordered set
    - Add least upper bound, greatest lower bound to partially ordered set
    - It's a lattice, so apply lattice rules!

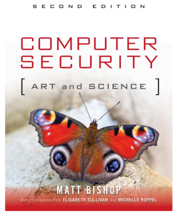


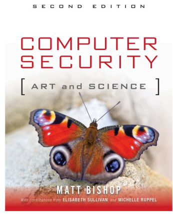
In Detail …

- $\forall x \in S_Q$: let $f(x) = \{ y \mid y \in S_Q \wedge y \leq_Q x \}$
  - Define $S_{QP} = \{ f(x) \mid x \in S_Q \}$
  - Define $\leq_{QP} = \{ (x, y) \mid x, y \in S_Q \wedge x \subseteq y \}$
    - S_{QP} partially ordered set under $\leq_{QP}$
    - f preserves order, so $y \leq_Q x$ iff $f(x) \leq_{QP} f(y)$
- Add upper, lower bounds
  - $S_{QP}' = S_{QP} \cup \{ S_Q, \varnothing \}$
  - Upper bound $ub(x, y) = \{ z \mid z \in S_{QP} \wedge x \subseteq z \wedge y \subseteq z \}$
  - Least upper bound $lub(x, y) = \cap ub(x, y)$
    - Lower bound, greatest lower bound defined analogously

And the Policy Is …

- Now (S_{QP}', $\leq_{QP}$) is lattice
- Information flow policy on quasi-ordered set emulates that of this lattice!



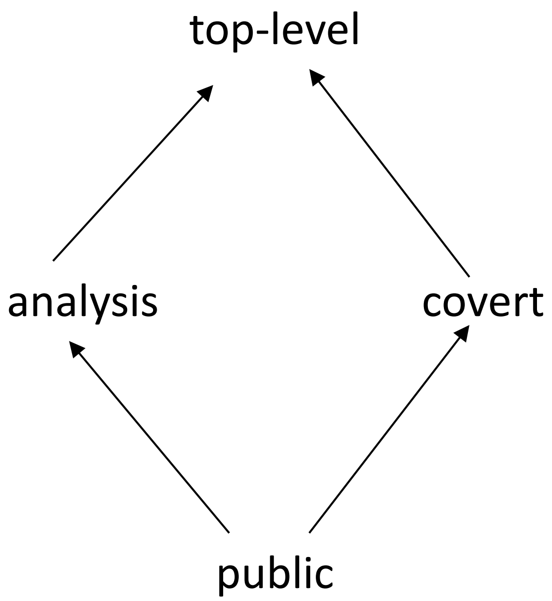


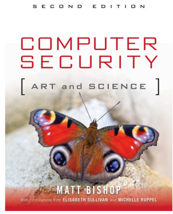
Nontransitive Flow Policies

- Government agency information flow policy (on next slide)
- Entities public relations officers PRO, analysts A, spymasters S
  - *confine*(PRO) = [public, analysis]
  - *confine*(A) = [analysis, top-level]
  - *confine*(S) = [covert, top-level]

Information Flow

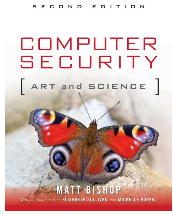
- By confinement flow model:
  - PRO ≤ A, A ≤ PRO
  - PRO ≤ S
  - A ≤ S, S ≤ A
- Data *cannot* flow to public relations officers; not transitive
  - S ≤ A, A ≤ PRO
  - S ≤ PRO is *false*





Transforming Into Lattice

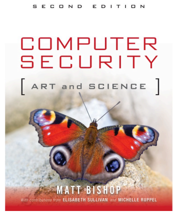
- Rough idea: apply a special mapping to generate a subset of the power set of the set of classes
  - Done so this set is partially ordered
  - Means it can be transformed into a lattice
- Can show this mapping preserves ordering relation
  - So it preserves non-orderings and non-transitivity of elements corresponding to those of original set



Dual Mapping

- $R = (SC_R, \leq_R, join_R)$ reflexive info flow policy
- $P = (S_P, \leq_P)$ ordered set
  - Define *dual mapping* functions $l_R, h_R: SC_R \rightarrow S_P$
    - $l_R(x) = \{ x \}$
    - $h_R(x) = \{ y \mid y \in SC_R \wedge y \leq_R x \}$
  - S_P contains subsets of SC_R; $\leq_P$ subset relation
  - Dual mapping function *order preserving* iff

$$(\forall a, b \in SC_R)[\ a \leq_R b \Leftrightarrow l_R(a) \leq_P h_R(b)\ ]$$



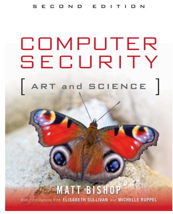
Theorem

Dual mapping from reflexive information flow policy R to ordered set P order-preserving

Proof sketch: all notation as before

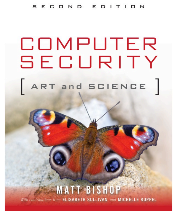
($\Rightarrow$) Let $a \leq_R b$. Then $a \in l_R(a)$, $a \in h_R(b)$, so $l_R(a) \subseteq h_R(b)$, or $l_R(a) \leq_P h_R(b)$

($\Leftarrow$) Let $l_R(a) \leq_P h_R(b)$. Then $l_R(a) \subseteq h_R(b)$. But $l_R(a) = \{ a \}$, so $a \in h_R(b)$, giving $a \leq_R b$



Information Flow Requirements

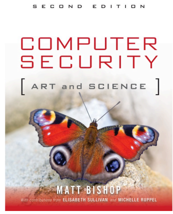
- Interpretation: let *confine*(x) = [$\underline{x}_L$, $\underline{x}_U$], consider class $\underline{y}$
  - Information can flow from x to element of $\underline{y}$ iff $\underline{x}_L \leq_R \underline{y}$, or $l_R(\underline{x}_L) \subseteq h_R(\underline{y})$
  - Information can flow from element of $\underline{y}$ to x iff $y \leq_R \underline{x}_U$, or $l_R(\underline{y}) \subseteq h_R(\underline{x}_U)$



Revisit Government Example

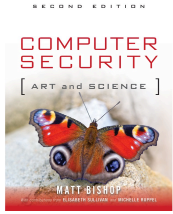
- Information flow policy is *R*
- Flow relationships among classes are:

public $\le_R$ public
public $\le_R$ analysis
public $\le_R$ covert
public $\le_R$ top-level
analysis $\le_R$ top-level
analysis $\le_R$ analysis
covert $\le_R$ covert
covert $\le_R$ top-level
top-level $\le_R$ top-level



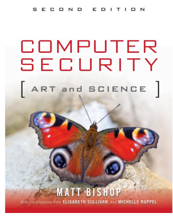
Dual Mapping of R

- Elements l_R, h_R:
  l_R(public) = { public }
  h_R(public = { public }
  l_R(analysis) = { analysis }
  h_R(analysis) = { public, analysis }
  l_R(covert) = { covert }
  h_R(covert) = { public, covert }
  l_R(top-level) = { top-level }
  h_R(top-level) = { public, analysis, covert, top-level }



confine

- Let *p* be entity of type PRO, *a* of type A, *s* of type S
- In terms of *P* (not *R*), we get:
  - *confine*(*p*) = [{ public }, { public, analysis }]
  - *confine*(*a*) = [{ analysis }, { public, analysis, covert, top-level }]
  - *confine*(*s*) = [{ covert }, { public, analysis, covert, top-level }]

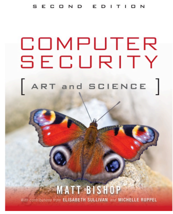


And the Flow Relations Are …

- $p \rightarrow a$ as $l_R(p) \subseteq h_R(a)$
    - $l_R(p)$ = { public }
    - $h_R(a)$ = { public, analysis, covert, top-level }
- Similarly: $a \rightarrow p$, $p \rightarrow s$, $a \rightarrow s$, $s \rightarrow a$
- But $s \rightarrow p$ is false as $l_R(s) \not\subset h_R(p)$
    - $l_R(s)$ = { covert }
    - $h_R(p)$ = { public, analysis }

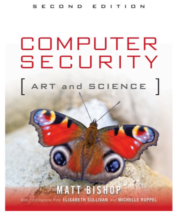
Analysis

- $(S_P, \leq_P)$ is a lattice, so it can be analyzed like a lattice policy
- Dual mapping preserves ordering, hence non-ordering and non-transitivity, of original policy
    - So results of analysis of $(S_P, \leq_P)$ can be mapped back into $(SC_R, \leq_R, join_R)$



Compiler-Based Mechanisms

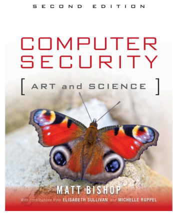
- Detect unauthorized information flows in a program during compilation
- Analysis not precise, but secure
  - If a flow *could* violate policy (but may not), it is unauthorized
  - No unauthorized path along which information could flow remains undetected
- Set of statements *certified* with respect 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



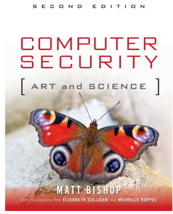
Declarations

- Notation:

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

  means *x* is an integer variable with security class at least *lub*{ A, B }, so *lub*{ A, B } ≤ $\underline{x}$

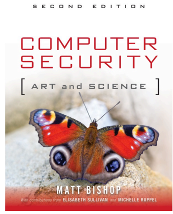
- Distinguished classes *Low*, *High*
  - Constants are always *Low*



Input Parameters

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

i_p: ***type*** **class** { $\mathtt{i}_\mathtt{p}$ }

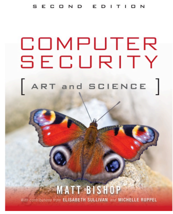


Output Parameters

- 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:

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

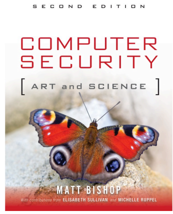
where r_i is class of *i*th input or input/output argument



Example

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

- Require $\underline{x} \le \underline{out}$ and $\underline{out} \le \underline{out}$



Array Elements

- Information flowing out:

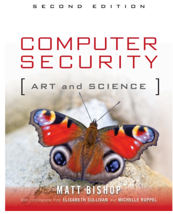
```
… := a[i]
```

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

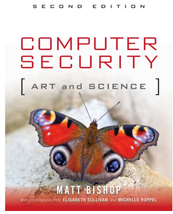
$x := y + z;$

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

More generally:

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

- the relation $\text{lub}\{ \underline{x}_1, \ldots, \text{x}_n \} \le \underline{y}$ must hold



Compound Statements

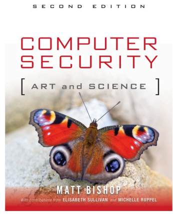
$x := y + z; a := b * c - x;$

- 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; … S_n;

- Each individual S_i must be secure



Conditional Statements

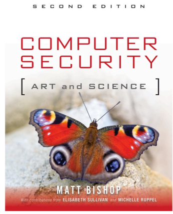
```
if x + y < z then a := b else d := b * c – x; end
```

- 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, …, 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

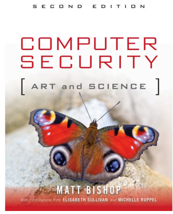
`while` $i < n$ `do begin` $a[i]$ `:=` $b[i]$; i `:=` $i + 1$; `end`

- Same ideas as for “if”, but must terminate

More generally:

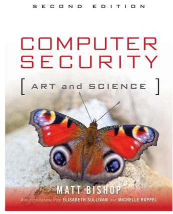
`while` $f(x_1, \ldots, x_n)$ `do` S;

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



Goto Statements

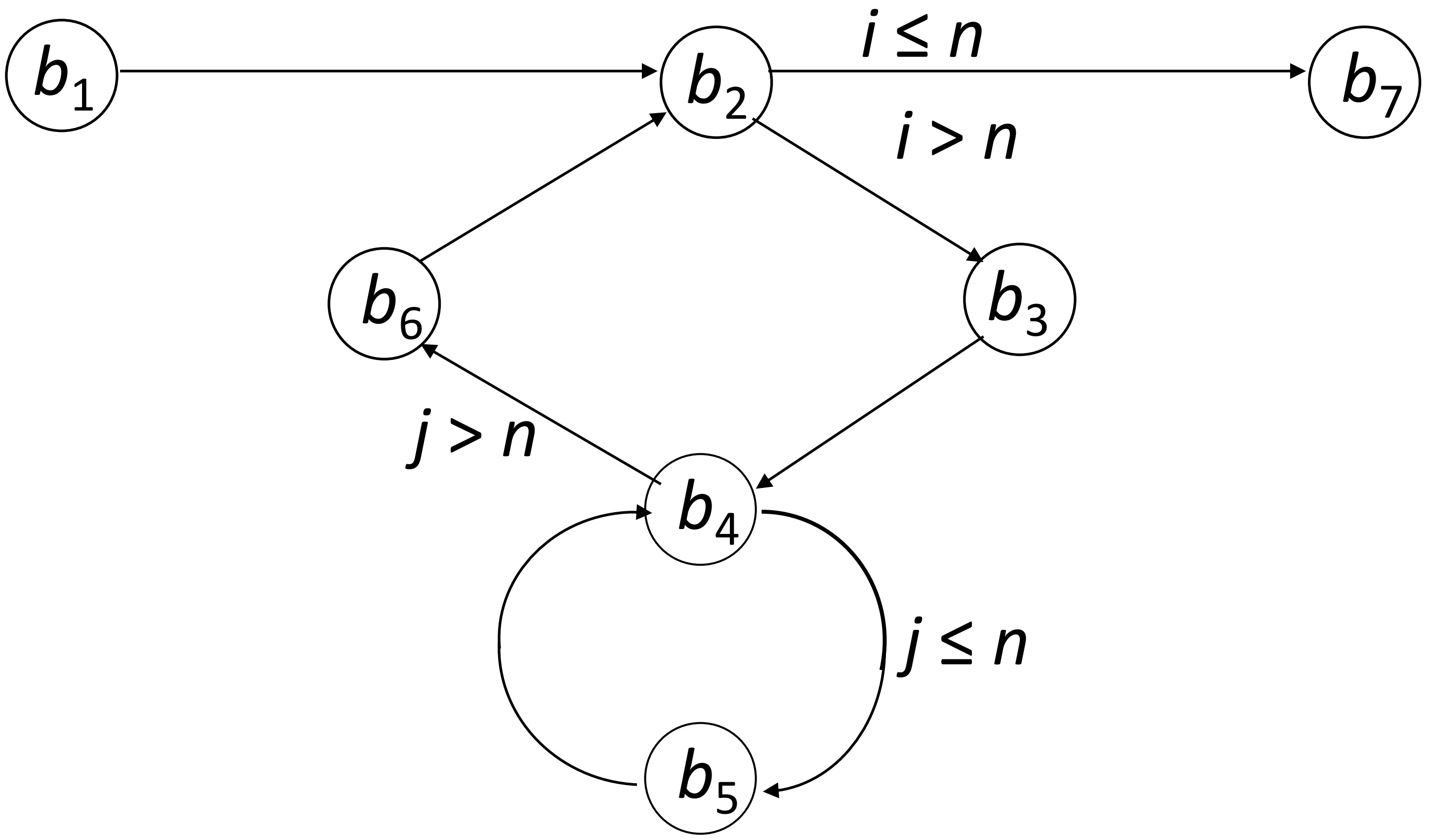
- No assignments
  - Hence no explicit flows
- Need to detect implicit flows
- *Basic block* is sequence of statements that have one entry point and one exit point
  - Control in block *always* flows from entry point to exit point

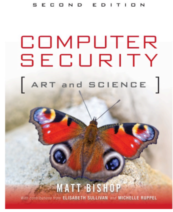


Example Program

```
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
$b_1$     i := 1;
$b_2$ L2: if i > 10 goto L7;
$b_3$     j := 1;
$b_4$ L4: if j > 10 then goto L6;
$b_5$     y[j][i] := x[i][j]; j := j + 1; goto L4;
$b_6$ L6: i := i + 1; goto L2;
$b_7$ L7:
end;
```

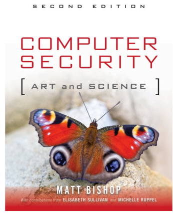
Flow of Control





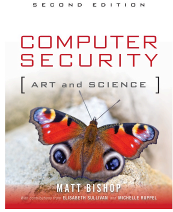
IFDs

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



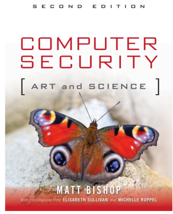
IFD Example

- 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



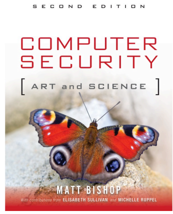
Requirements

- 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$\{ \underline{x}_{i1}, \ldots, \underline{x}_{in} \} \leq$ glb$\{ \underline{y} \mid y$ target of assignment in $B_i \}$



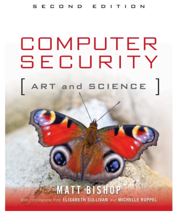
Example of Requirements

- 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: $\text{lub}\{\, \underline{x[i][j]}, \underline{i}, \underline{j} \,\} \le \underline{y[j][i]}$ }; $\text{lub}\{\, Low, \underline{j} \,\} \le \underline{j}$
  - Combining, $\text{lub}\{\, \underline{x[i][j]}, \underline{i}, \underline{j} \,\} \le \underline{y[j][i]}$ }
  - From declarations, true when $\text{lub}\{\, \underline{x}, \underline{i} \,\} \le \underline{y}$
- $B_2 = \{b_3, b_4, b_5, b_6\}$
  - Assignments to i, j, $y[j][i]$; conditional is $i \le 10$
  - Requires $\underline{i} \le \text{glb}\{\, \underline{i}, \underline{j}, \underline{y[j][i]} \,\}$
  - 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 $\underline{j} \le \text{glb}\{ \underline{j}, \underline{y[j][i]} \}$
  - From declarations, means $\underline{i} \le \underline{y}$
- Result:
  - Combine $\text{lub}\{ \underline{x}, \underline{i} \} \le \underline{y}$; $\underline{i} \le \underline{y}$; $\underline{i} \le \underline{y}$
  - Requirement is $\text{lub}\{ \underline{x}, \underline{i} \} \le \underline{y}$



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:

$\textbf{proc}\ pn(i_1,\ \ldots,\ i_m\textbf{: int; var}\ o_1,\ \ldots,\ o_n\textbf{: int); begin}\ S\ \textbf{end;}$

- 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 $\underline{y}_j \le \underline{y}_k$

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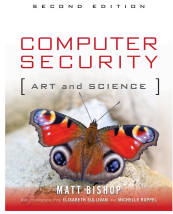
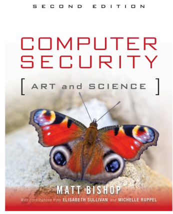


Exceptions

```
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
```

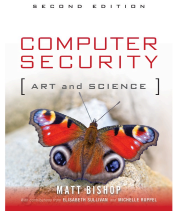


Exceptions (*cont*)

- When sum overflows, integer overflow trap
  - Procedure exits
  - Value of *x* is MAXINT/*y*
  - Information 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;
```

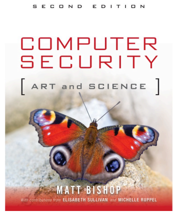
  - Now information flows from *sum* to *z*, meaning $\underline{sum} \le \underline{z}$
  - This is false ($\underline{sum}$ = { x } dominates $\underline{z}$ = Low)



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:

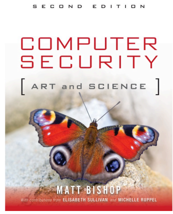
```
wait(x):   if x = 0 then block until x > 0; x := x – 1;
signal(x): x := x + 1;
```

- *x* is semaphore, a shared variable
- Both executed atomically

Consider statement

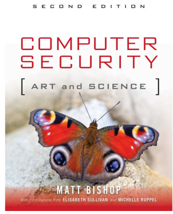
```
wait(sem); x := x + 1;
```

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



Flow Requirements

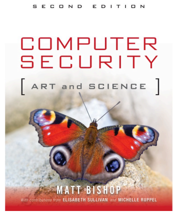
- Semaphores in *signal* irrelevant
  - Don't affect information flow in that process
- Statement S is a *wait*
  - shared(S): set of shared variables read
    - Idea: information flows out of variables in shared(S)
  - fglb(S): glb of assignment targets *following* S
  - So, requirement is shared(S)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



Example

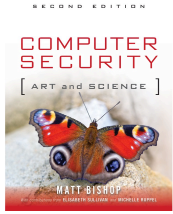
```
begin
    $x$ := $y$ + $z$;            (* $S_1$ *)
    wait($sem$);                 (* $S_2$ *)
    $a$ := $b$ * $c$ – $x$;      (* $S_3$ *)
end
```

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



Concurrent Loops

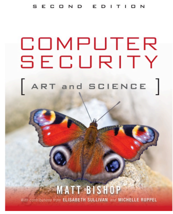
- Similar, but wait in loop affects *all* statements in loop
  - Because if flow of control loops, statements in loop before wait may be executed after wait
- Requirements
  - Loop terminates
  - All statements $S_1, \ldots, S_n$ in loop secure
  - $\text{lub}\{\ \underline{\text{shared}(S_1)}, \ldots,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

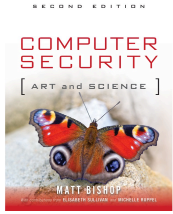
- Conditions for this to be secure:
    - Loop terminates, so this condition met
    - S_1 secure if $\text{lub}\{ \underline{i}, \underline{item} \} \le \underline{a[i]}$
    - S_2 secure if $\underline{sem} \le \underline{i}$ and $\underline{sem} \le \underline{a[i]}$
    - S_3 trivially secure



cobegin/coend

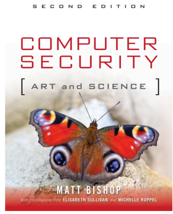
```
cobegin
        x := y + z;           (* S1 *)
        a := b * c – y;       (* S2 *)
coend
```

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



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

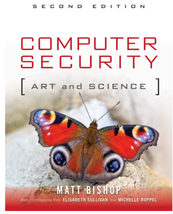


Execution-Based Mechanisms

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

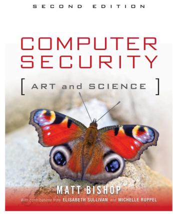
```
if x = 1 then y := a;
```

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



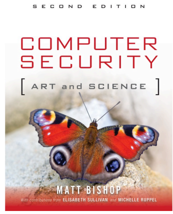
Fenton’s Data Mark Machine

- 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



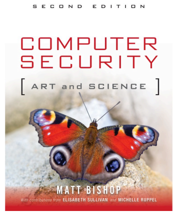
Instruction Description

- *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

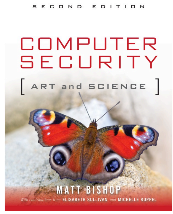
- $x := x + 1$ (increment)
  - Same as:
    ```
    if $\underline{PC} \le \underline{x}$ then $x := x + 1$ else skip
    ```
- **if** $x = 0$ **then goto** n **else** $x := x - 1$ (branch and save PC on stack)
  - Same as:
    ```
    if $x = 0$ then begin
      push($PC$, $\underline{PC}$); $\underline{PC}$ := lub{$\underline{PC}$, $\underline{x}$}; 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 $skip$
```

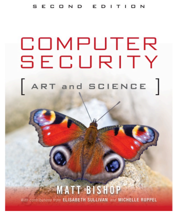


More Instructions

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

    pop(*PC*, $\underline{PC}$);
- **halt** (stop)
  - Same as:

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

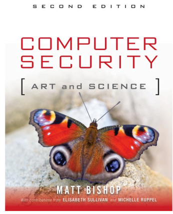


Example Program

```
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
```

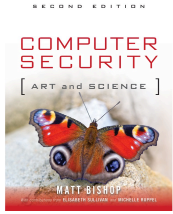
Initially $x = 0$ or $x = 1$, $y = 0$, $z = 0$

Program copies value of x to y



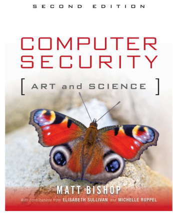
Example Execution

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



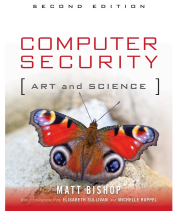
Handling Errors

- 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

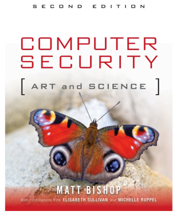
- Up to now, classes fixed
    - Check relationships on assignment, etc.
- Consider variable classes
    - Fenton’s Data Mark Machine does this for $\underline{PC}$
    - On assignment of form $y := f(x_1, \ldots, x_n)$, $\underline{y}$ changed to lub$\{ \underline{x}_1, \ldots, \underline{x}_n \}$
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



Example Program

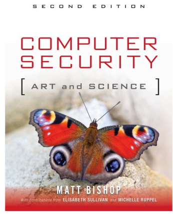
```
(* Copy value from x to y. Initially, x is 0 or 1 *)
proc copy(x: integer class { x };
               var y: integer class { y })
var z: integer class variable { Low };
begin
  y := 0;
  z := 0;
  if x = 0 then z := 1;
  if z = 0 then y := 1;
end;
```

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



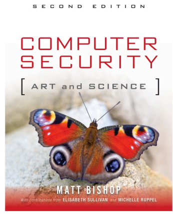
Analysis of Example

- $x = 0$
  - `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 $\text{lub}\{\text{Low}, \underline{z}\} \le \underline{y}$
  - So on exit, $y = 1$
- Information flowed from $\underline{x}$ to $\underline{y}$ even though $\underline{y} < \underline{x}$



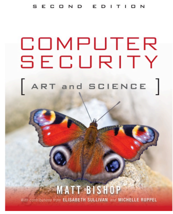
Handling This (1)

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



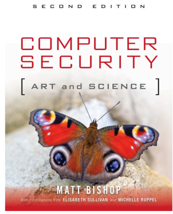
Handling This (2)

- 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 $\underline{z} \le \underline{y}$, fails, as $\underline{z} = \underline{x}$ from previous statement, and $\underline{y} \le \underline{x}$



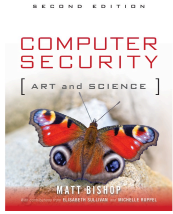
Handling This (3)

- 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 $\underline{x} \le \underline{z}$
  - This holds if and only if $\underline{x}$ = Low
    - Not possible as $\underline{y} < \underline{x}$ = Low by assumption and there is no such class



Integrity Mechanisms

- The above also works with Biba, as it is mathematical dual of Bell-LaPadula
- All constraints are simply duals of confidentiality-based ones presented above



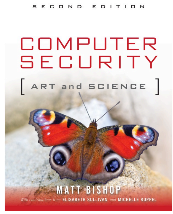
Example 1

For information flow of assignment statement:

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

the relation $\text{glb}\{ \underline{x}_1, \ldots, x_n \} \leq \underline{y}$ must hold

- Why? Because information flows from $x_1, \ldots, x_n$ to y, and under Biba, information must flow from a higher (or equal) class to a lower one



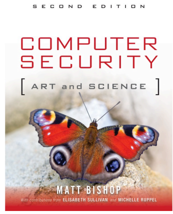
Example 2

For information flow of conditional statement:

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

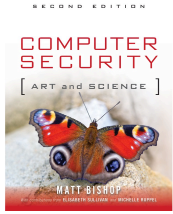
then the following must hold:

- S_1, S_2 must satisfy integrity constraints
- glb$\{ \underline{x}_1, \ldots, \underline{x}_n \} \geq$ lub$\{\underline{y} \mid y$ target of assignment in $S_1, S_2 \}$



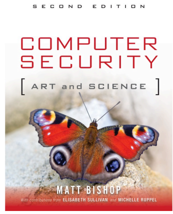
Example Information Flow Control Systems

- Use access controls of various types to inhibit information flows
- Privacy and Android Cell Phones
  - Analyzes data being sent from the phone
- Firewalls



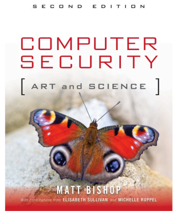
Privacy and Android Cell Phones

- Many commercial apps use advertising libraries to monitor clicks, fetch ads, display them
  - So they send information, ostensibly to help tailor advertising to you
- Many apps ask to have full access to phone, data
  - This is because of complexity of permission structure of Android system
- Ads displayed with privileges of app
  - And if they use Javascript, that executes with those privileges
  - So if it has full access privilege, it can send contact lists, other information to others
- Information flow problem as information is flowing from phone to external party



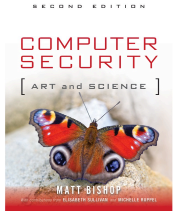
Analyzing Android Flows

- Android based on Linux
  - App executables in bytecode format (Dalvik executables, or DEX) and run in Dalvik VM
  - Apps event driven
  - Apps use system libraries to do many of their functions
  - Binder subsystem controls interprocess communication
- Analysis uses 2 security levels, *untainted* and *tainted*
  - No categories, and *tainted* < *untainted*



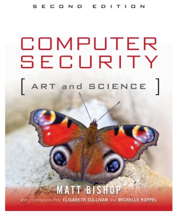
TaintDroid: Checking Information Flows

- All objects tagged *tainted* or *untainted*
    - Interpreters, Binder augmented to handle tags
- Android native libraries trusted
    - Those communicating externally are *taint sinks*
- When untrusted app invokes a taint sink library, taint tag of data is recorded
- Taint tags assigned to external variables, library return values
    - These are assigned based on knowledge of what native code does
- Files have single taint tag, updated when file is written
- Database queries retrieve information, so tag determined by database query responder



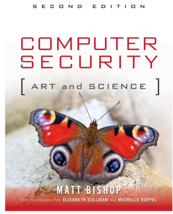
TaintDroid: Checking Information Flows

- Information from phone sensor may be sensitive; if so, *tainted*
  - TaintDroid determines this from characteristics of information
- Experiment 1 (2010): select 30 popular apps out of a set of 358 that required permission to access Internet, phone location, camera, or microphone; also could access cell phone information
  - 105 network connections accessed *tainted* data
  - 2 sent phone identification information to a server
  - 9 sent device identifiers to third parties, and 2 didn’t tell user
  - 15 sent location information to third parties, none told user
  - No false positives



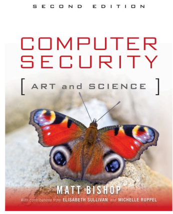
TaintDroid: Checking Information Flows

- Experiment 2 (2010): revisit 18 out of the 30 apps (others did not run on current version of Android)
  - 3 still sent location information to third parties
  - 8 sent device identification information to third parties without consent
    - 3 of these did so in 2010 experiment
    - 5 were new
  - 2 new flows that could reveal *tainted* data
  - No false positives



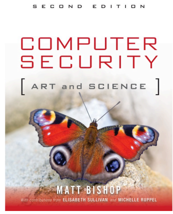
Firewalls

- Host that mediates access to a network
  - Allows, disallows accesses based on configuration and type of access
- Example: block Conficker worm
  - Conficker connects to botnet, which can use system for many purposes
    - Spreads through a vulnerability in a particular network service
  - Firewall analyze packets using that service remotely, and look for Conficker and its variants
    - If found, packets discarded, and other actions may be taken
  - Conficker also generates list of host names, tried to contact botnets at those hosts
    - As set of domains known, firewall can also block outbound traffic to those hosts



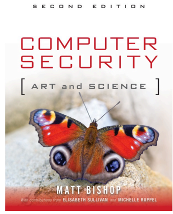
Filtering Firewalls

- *A*ccess control based on attributes of packets and packet headers
  - Such as destination address, port numbers, options, etc.
  - Also called a *packet filtering firewall*
  - Does not control access based on content
  - Examples: routers, other infrastructure systems



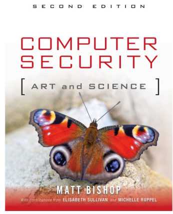
Proxy

- Intermediate agent or server acting on behalf of endpoint without allowing a direct connection between the two endpoints
  - So each endpoint talks to proxy, thinking it is talking to other endpoint
  - Proxy decides whether to forward messages, and whether to alter them



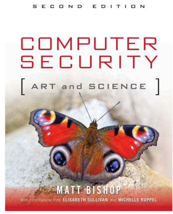
Proxy Firewall

- Access control done with proxies
  - Usually bases access control on content as well as source, destination addresses, etc.
  - Also called an *applications level* or *application level firewall*
  - Example: virus checking in electronic mail
    - Incoming mail goes to proxy firewall
    - Proxy firewall receives mail, scans it
    - If no virus, mail forwarded to destination
    - If virus, mail rejected or disinfected before forwarding



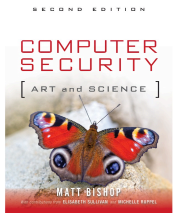
Example

- Want to scan incoming email for malware
- Firewall acts as recipient, gets packets making up message and reassembles the message
  - It then scans the message for malware
  - If none, message forwarded
  - If some found, mail is discarded (or some other appropriate action)
- As email reassembled at firewall by a mail agent acting on behalf of mail agent at destination, it’s a proxy firewall (application layer firewall)



Stateful Firewall

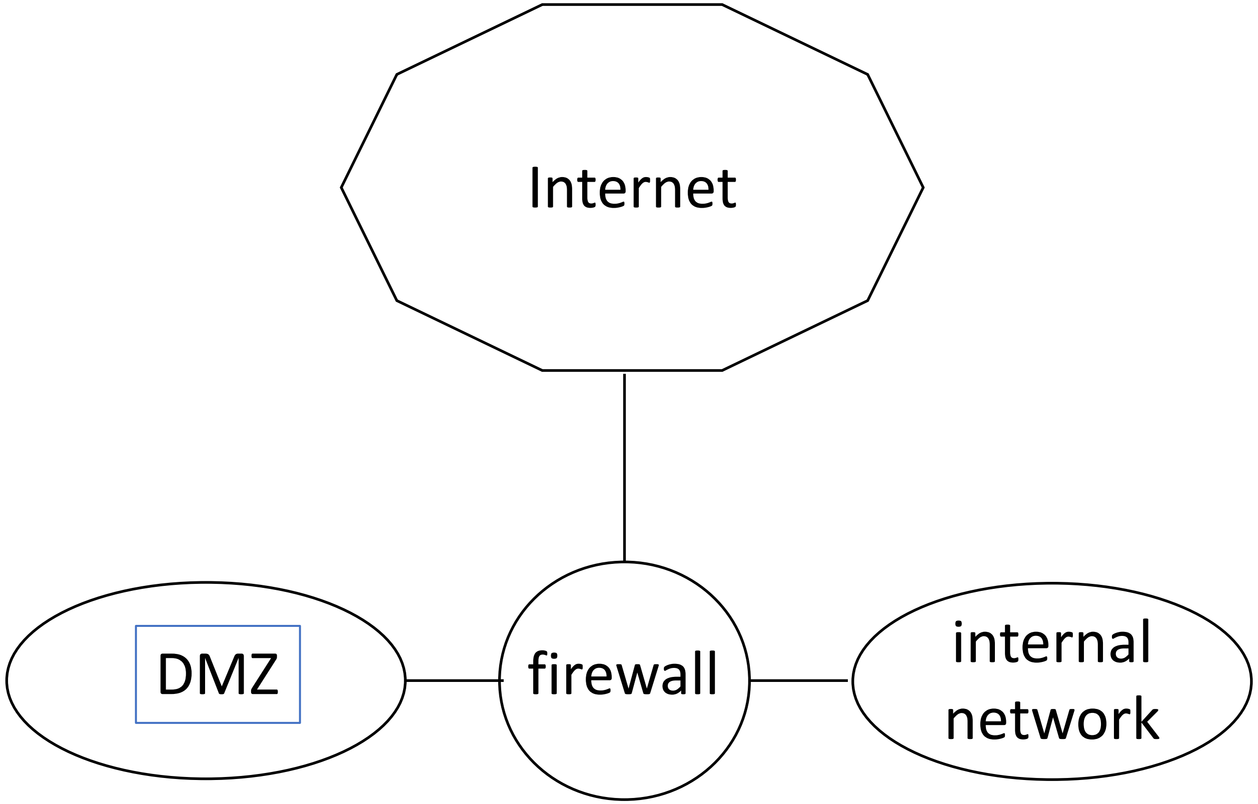
- Keeps track of the state of each connection
- Similar to a proxy firewall
  - No proxies involved, but this can examine contents of connections
  - Analyzes each packet, keeps track of state
  - When state indicates an attack, connection blocked or some other appropriate action taken



Network Organization: DMZ

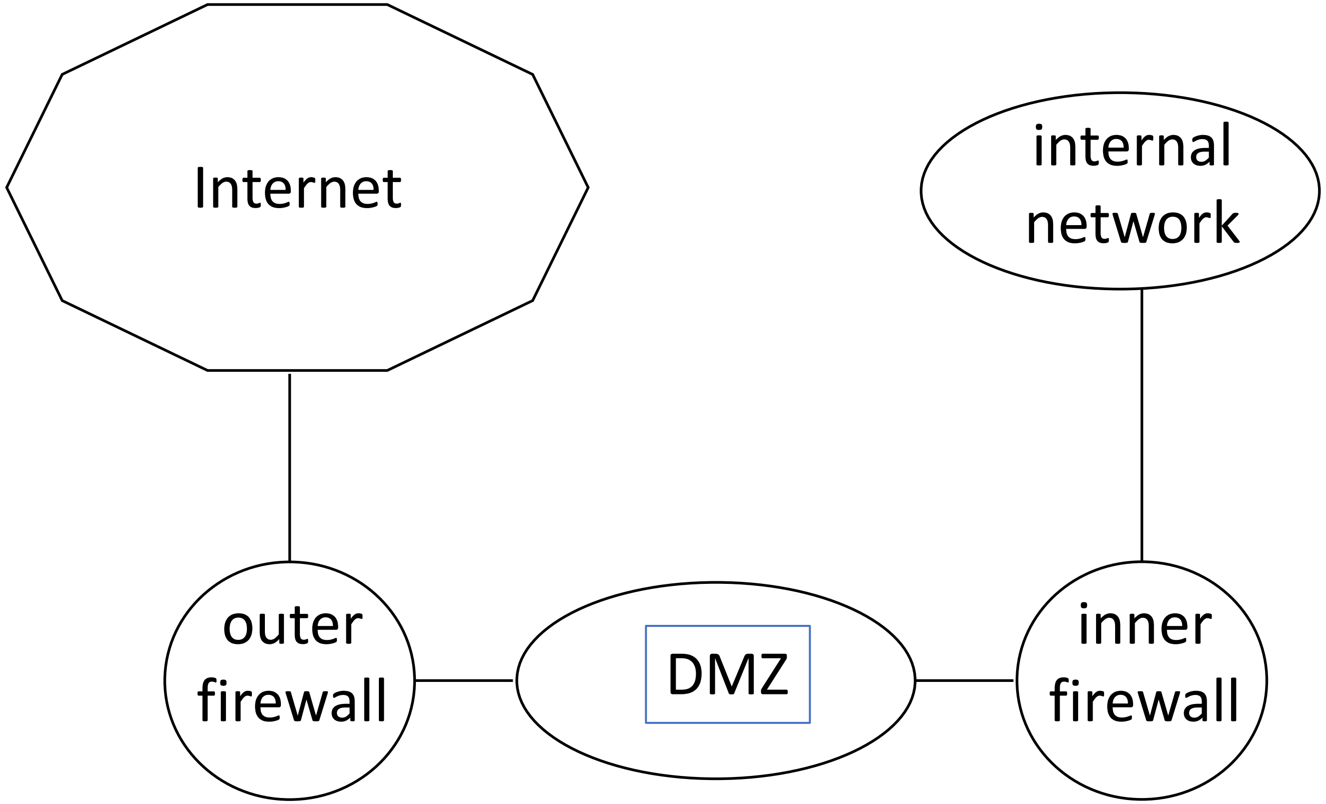
- DMZ is portion of network separating a purely internal network from external network
- Usually put systems that need to connect to the Internet here
- Firewall separates DMZ from purely internal network
- Firewall controls what information is allowed to flow through it
    - Control is bidirectional; it control flow in both directions

One Setup of DMZ

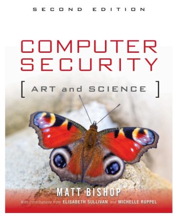


One dual-homed firewall that routes messages to internal network or DMZ as appropriate

Another Setup of DMZ



Two firewalls, one (outer firewall) connected to the Internet, the other (inner firewall) connected to internal network, and the DMZ is between the firewalls



Key Points

- Both amount of information, direction of flow important
    - Flows can be explicit or implicit
- Analysis assumes lattice model
    - Non-lattices can be embedded in lattices
- Compiler-based checks flows at compile time
- Execution-based checks flows at run time
- Analysis can be for confidentiality, integrity, or both