Program Analysis

Information Flow Analysis

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Warm-up Quiz

```
var a;
var a, a;
var a, a, a = a;
a = eval("var a;")
a = function a(a, a) {
    return a;
}
a = a(null, a);
console.log(a.name);
```

Warm-up Quiz

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var a, a;
var a, a, a = a;
a = eval("var a;")
a = function a(a, a) {
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}
a = a(null, a);
console.log(a.name);
```

Result: a

Warm-up Quiz

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var a;
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a = eval("var a;")
a = function a(a, a) {
    return a;
}
a = a(null, a);
console.log(a.name);
```

a is a function that returns the second argument, i.e., the function itself

Result: a

Outline

1. **Introduction**
2. **Information Flow Policy**
3. **Analyzing Information Flows**

Mostly based on these papers:

- *A Lattice Model of Secure Information Flow*, Denning, Comm ACM, 1976
- *Dytan: A Generic Dynamic Taint Analysis Framework*, Clause et al., ISSTA 2007

Secure Computing Systems

- **Overall goal: Secure the data manipulated by a computing system**
- **Enforce a security policy**
  - Confidentiality: Secret data does not leak to non-secret places
  - Integrity: High-integrity data is not influenced by low-integrity data

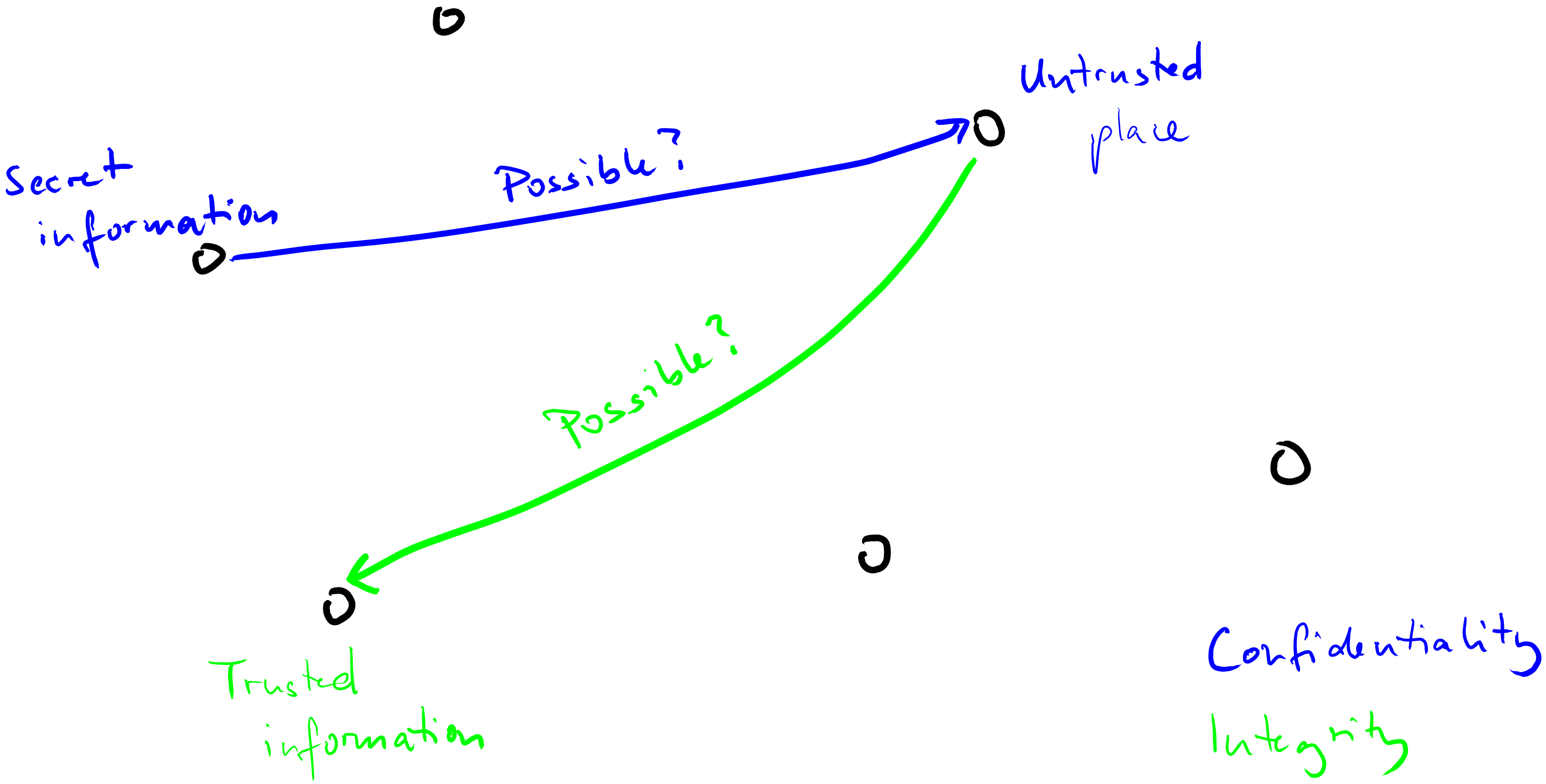
Information Flow

- **Goal of information flow analysis:**

  Check whether information from one ”place” propagates to another ”place”
  - For program analysis, ”place” means, e.g., code location or variable

- **Complements techniques that impose limits on releasing information**
  - Access control lists
  - Cryptography

o ... "Places" in a program that hold data



Example: Confidentiality

Credit card number should not leak to `visible`

```
var creditCardNb = 1234;
var x = creditCardNb;
var visible = false;
if (x > 1000) {
  visible = true;
}
```

Example: Confidentiality

Credit card number should not leak to `visible`

```
var creditCardNb = 1234;
var x = creditCardNb;
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if (x > 1000) {
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}
```

Secret information propagates to `x`

Secret information (partly) propagates to `visible`

Example: Integrity

`userInput` should not influence who becomes president

```
var designatedPresident = "Michael";
var x = userInput();
var designatedPresident = x;
```

Example: Integrity

`userInput` should not influence who becomes president

```
var designatedPresident = "Michael";
var x = userInput();
var designatedPresident = x;
```

Low-integrity information propagates to high-integrity variable

Example: Integrity

`userInput` should not influence who becomes president

```
var designatedPresident = "Michael";
var x = userInput();
if (x.length === 5) {
  var designatedPresident = "Paul";
}
```

Example: Integrity

`userInput` should not influence who becomes president

```
var designatedPresident = "Michael";
var x = userInput();
if (x.length === 5) {
  var designatedPresident = "Paul";
}
```

Low-integrity information propagates to high-integrity variable

Confidentiality vs. Integrity

Confidentiality and integrity are dual problems for information flow analysis

(Focus of this lecture: Confidentiality)

Tracking Security Labels

How to analyze the flow of information?

- **Assign to each value some meta information that tracks the secrecy of the value**
- **Propagate meta information on program operations**

Example

secret

```
creditCardNb = 1234

x = creditCardNb

visible = false

if (x > 1000) {
    visible = true
}
```

_ _ _ _ : contains a secret value

Non-Interference

Property that information flow analysis aims to ensure:

Confidential data does not interfere with public data

- Variation of confidential input does not cause a variation of public output
- Attacker cannot observe any difference between two executions that differ only in their confidential input

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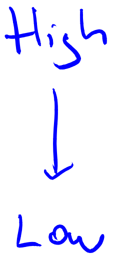
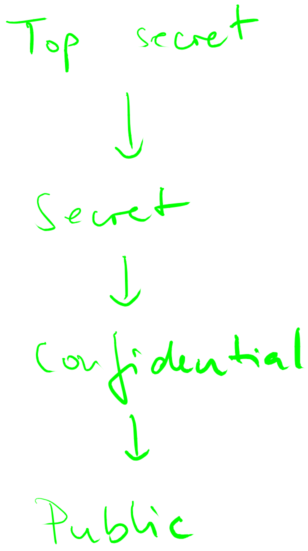
Lattice of Security Labels

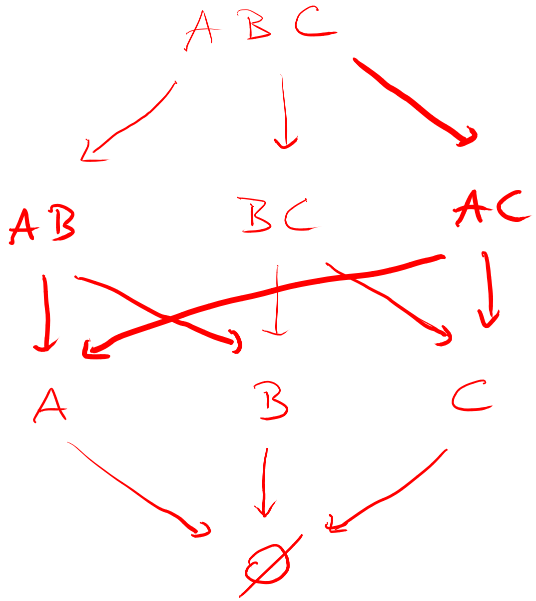
How to represent different levels of secrecy?

- Set of security labels
- Arranged in a universally bounded lattice

Lattice: Examples







(Arrows go from more secret security classes
to less secret security classes)

Universally Bounded Lattices

Tuple $(S, \rightarrow, \bot, \top, \oplus, \otimes)$

where S .. set of security classes

$\{A, B, C, AB, BC, AC, ABC, \emptyset\}$

$\rightarrow$ .. partial order

(see figure)

$\bot$ .. lower bound $\emptyset$

$\top$ .. upper bound ABC.

$\oplus$ .. least upper bound operator, $S \times S \rightarrow S$

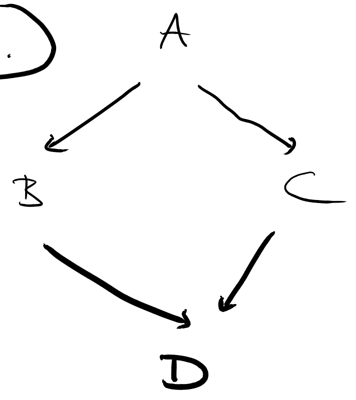
union, e.g. $AB \oplus A = AB$, $\emptyset \oplus AC \rightarrow AC$

$\otimes$ .. greatest lower bound operator, $S \times S \rightarrow S$

intersection, e.g. $ABC \otimes C = C$

Quiz: Which of these are universally bounded lattices?

1.

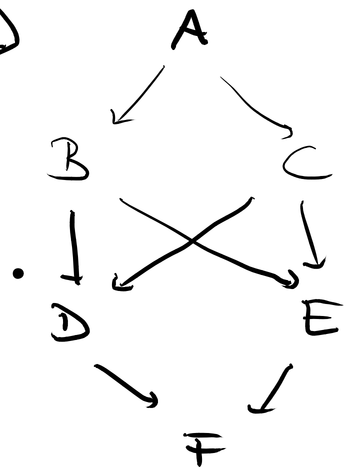


✓

2.

✓

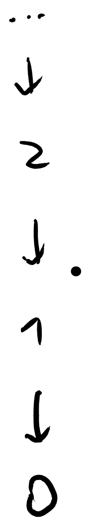
3.



D ⊕ E = ?

- three common upper bounds (A, B, C)
- but none is <u>the</u> least upper bound

4.



no upper bound (infinite)

Information Flow Policy

Policy specifies secrecy of values and which flows are allowed:

- Lattice of security classes
- Sources of secret information
- Untrusted sinks

Goal:
No flow from source to sink

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Goal: No flow from source to sink

Declassification

- ”No flow from high to low” is impractical
- E.g., code that checks password against a hash value propagates information to subsequent statements
  But: This is intended

```
var password = ..  // secret
if (hash(password) === 23) {
  // continue normal program execution
} else {
  // display message: incorrect password
}
```

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Declassification: Mechanism to remove or lower security class of a value

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Analyzing Information Flows

Given an information flow policy, analysis checks for policy violations

Applications:

- Detect vulnerable code (e.g, potential SQL injections)
- Detect malicious code (e.g., privacy violations)
- Check if program behaves as expected (e.g., secret data should never be written to console)

Explicit vs. Implicit Flows

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- **Implicit flows**: Caused by control flow dependence

```
var creditCardNb = 1234;
var x = creditCardNb;
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```

Explicit flow from `creditCardNb` to `x`

Implicit flow from `x > 1000` to `visible`

Explicit vs. Implicit Flows

- **Explicit flows: Caused by data flow dependence**

  Some analyses consider only these

- **Implicit flows: Caused by control flow dependence**

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var creditCardNb = 1234;
var x = creditCardNb;
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Explicit flow from `creditCardNb` to `x`

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Static and Dynamic Analysis

- **Static information flow analysis**
  - Overapproximate all possible data and control flow dependences
  - Result: Whether information may flow from secret source to untrusted sink
- **Dynamic information flow analysis**
  - Associate security labels (”taint markings”) with memory locations
  - Propagate labels at runtime

Static and Dynamic Analysis

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Focus of rest of this lecture

Taint Sources and Sinks

- **Possible sources**:
  - Variables
  - Return values of a particular function
  - Data from a particular I/O stream

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  - Instructions of a particular type (e.g., jump instructions)

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  - Instructions of a particular type (e.g., jump instructions)

Report illegal flow if taint marking flows to a sink to which it should not flow

Taint Propagation

1) Explicit flows

For every operation that produces a new value, propagate labels of inputs to label of output:

$$label(result) \leftarrow label(inp_1) \oplus ... \oplus label(inp_k)$$

Taint Propagation (2)

2) Implicit flows

- Maintain security stack S: Labels of all values that influence the current flow of control
- When x influences a branch decision at location loc, push $label(x)$ on S
- When control flow reaches immediate post-dominator of loc, pop $label(x)$ from S
- When an operation is executed while S is non-empty, consider all labels on S as input to the operation

Example 1

Policy:
- security classes: public, secret
- source: variable "creditCardNb"
- sink: variable "visible"

```
creditCardNb = 1234
x = creditCardNb
visible = false
if (x > 1000) {
    visible = true
}
```

- (creditCardNb = 1234) ← label(creditCardNb) = secret
- (x = creditCardNb) ← explicit flow: label(x) = secret
- (visible = false) ← label(visible) = public
- (if (x > 1000)) ← produce intermediate value b
  label(b) = label(x) ⊕ label(1000)
  = secret ⊕ public = secret
- (visible = true) ← push "secret" onto S
  label(visible) = secret ⊕ label(true)
  = secret ⊕ public = secret
  → violation of policy

Example 2: Quiz

```
var x = getX();
var y = x + 5;
var z = true;
if (y === 10)
  z = false;
foo(z);
```

Policy:

- Security classes: public, secret
- Source: `getX()`
- Sink: `foo()`

Suppose that `getX` returns 5. Write down the labels after each operation.

Is there a policy violation?

Example 2

x = getX()	←	label(x) = secret
y = x + 5	←	label(y) = secret ⊕ public = secret
z = true	←	label(z) = public
if (y == 10)	←	push "secret" to S
z = false	←	label(z) = secret ⊕ public = secret
	←	pop "secret" from S
foo(z)	←	violation !

Hidden Implicit Flows

- Implicit flows may happen even though a branch is not executed
- Approach explained so far will miss such ”hidden” flows

```
// label(x) = public, label(secret) = private
var x = false;
if (secret)
  x = true;
```

Hidden Implicit Flows

- Implicit flows may happen even though a branch is not executed
- Approach explained so far will miss such "hidden" flows

```
// label(x) = public, label(secret) = private
var x = false;
if (secret)
  x = true;
```

Copies `secret` into `x`

But: Execution where `secret` is `false` does not propagate anything

Hidden Implicit Flows (2)

Approach to reveal hidden flows:

For every conditional with branches b_1 and b_2:

- Conservatively overapproximate which values may be defined in b_1
- Add spurious definitions into b_2

Hidden Implicit Flows (2)

Approach to reveal hidden flows:

For every conditional with branches b_1 and b_2:

- Conservatively overapproximate which values may be defined in b_1
- Add spurious definitions into b_2

```
var x = false;
if (secret)
  x = true;
else
  x = x;    // spurious definition
```

All executions propagate ”secret” label to `x`

Implementation in Dytan

Dynamic information flow analysis for x86 binaries

- Taint markings stored as bit vectors
- One bit vector per byte of memory
- Propagation implemented via instrumentation (i.e., add instructions to existing program)
- Computes immediate post-dominators via static control flow graph

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