Program Testing and Analysis:

Slicing (Part 2)

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Warm-up Quiz

What does the following code print?

```
var x = 23;
function f() { console.log(this.x); }
var obj = Object.create({ f: f });
obj.x = 42;
f();
obj.f();
```

23	42	23	42
23	42	42	23

Warm-up Quiz

What does the following code print?

```
var x = 23;
function f() { console.log(this.x); }
var obj = Object.create({ f: f });
obj.x = 42;
f();
obj.f();
```

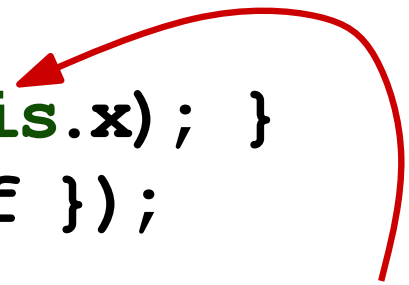
`obj`'s prototype has method `f`

23	42	23	42
23	42	42	23

Warm-up Quiz

What does the following code print?

```
var x = 23;
function f() { console.log(this.x); }
var obj = Object.create({ f: f });
obj.x = 42;
f();
obj.f();
```



`this` is determined at call site:

- Simple call: `global`
- Object method: base object

23	42	23	42
23	42	42	23

Slicing: Outline

1. **Introduction**
2. **Static Slicing**
3. **Thin Slicing**
4. **Dynamic Slicing** 

Mostly based on these papers:

- *Program Slicing*, Weiser., IEEE TSE, 1984
- *Thin Slicing*, Sridharan et al., PLDI 2007
- *Dynamic Program Slicing*, Agrawal and Horgan, PLDI 1990
- *A Survey of Program Slicing Techniques*, Tip, J Prog Lang 1995

Dynamic Slice (Simple Approach)

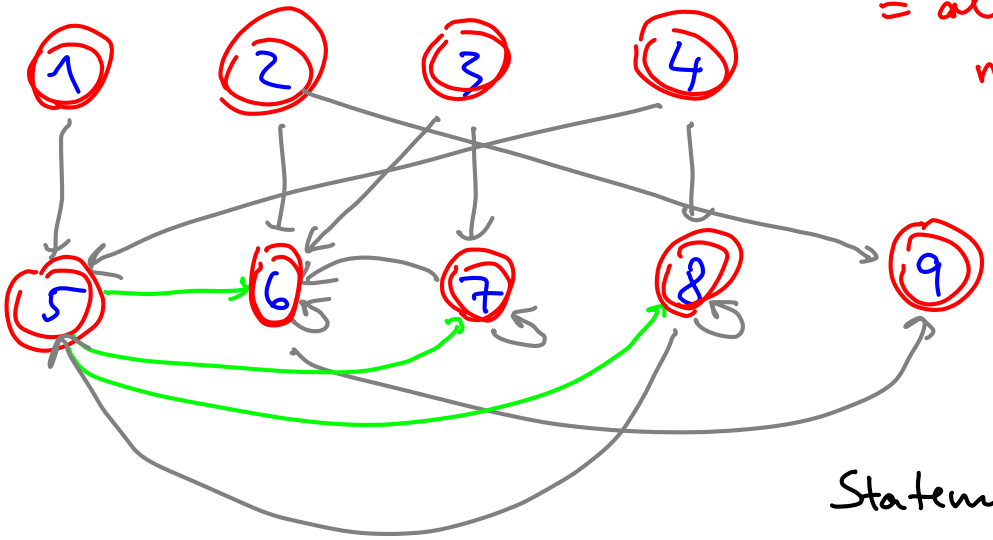
- **Given: Execution history**
  - Sequence of PDG nodes that are executed
- **Slice for statement n and variable v:**
  - Keep PDG nodes only if there are in history
  - Use static slicing approach (= graph reachability) on reduced PDG

Example 2

```
1  var n = readInput();
2  var z = 0;
3  var y = 0;
4  var i = 1;
5  while (i <= n) {
6    z = z + y;
7    y = y + 1;
8    i = i + 1;
   }
9  console.log(z);
```

Input: n = 1

History: 1, 2, 3, 4, 5, 6, 7, 8, 5, 9



○ .. in history

◎ .. slice (9, {z})
= all statements

BUT:
Statement 7 is not relevant!

Limitations of Simple Approach

- Multiple occurrences of a single statement are represented as a single PDG node
- Difference occurrences of a statement may have different dependences
  - All occurrences get conflated
- Slices may be larger than necessary

Dynamic Slice (Revised Approach)

Dynamic dependence graph

- Nodes: Occurrences of nodes of static PDG
- Edges: Dynamic data and control flow dependences

Slice for statement n and variables V that are defined or used at n:

- Compute nodes S_{dyn} that can reach any of the nodes that represent occurrences of n
- Slice = statements with at least one node in S_{dyn}

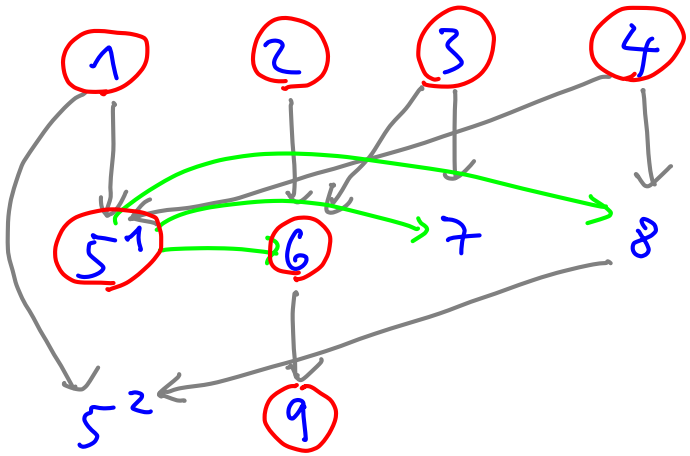
Example 2 (Revised approach)

```
1 var n = readInput();
2 var z = 0;
3 var y = 0;
4 var i = 1;
5 while (i <= n) {
6   z = z + y;
7   y = y + 1;
8   i = i + 1;
  }
9 console.log(z);
```

Input : n = 1

History: 1, 2, 3, 4, 5, 6, 7, 8, 5, 9

0 .. slice (9, {z})



Discussion: Dynamic Slicing

- May yield a program that, if executed, does not give the same value for the slicing criterion than the original program
- Instead: Focuses on isolating statements that affect a particular value
  - Useful, e.g., for debugging and program understanding
- Other approaches exist, see F. Tip's survey for an overview

Slicing: Summary

- Program slicing: Extract subset of statements for a particular purpose
  - Debugging, program understanding, change impact analysis, parallelization
- Various techniques
  - Traditional static slicing: Executable but potentially very large slice
  - Thin slicing: Focus on producer statements, reveal explainer statements on demand
  - Dynamic slicing: Useful for understanding behavior of particular execution

Program Testing and Analysis: Information Flow Analysis

Dr. Michael Pradel

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Outline

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

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

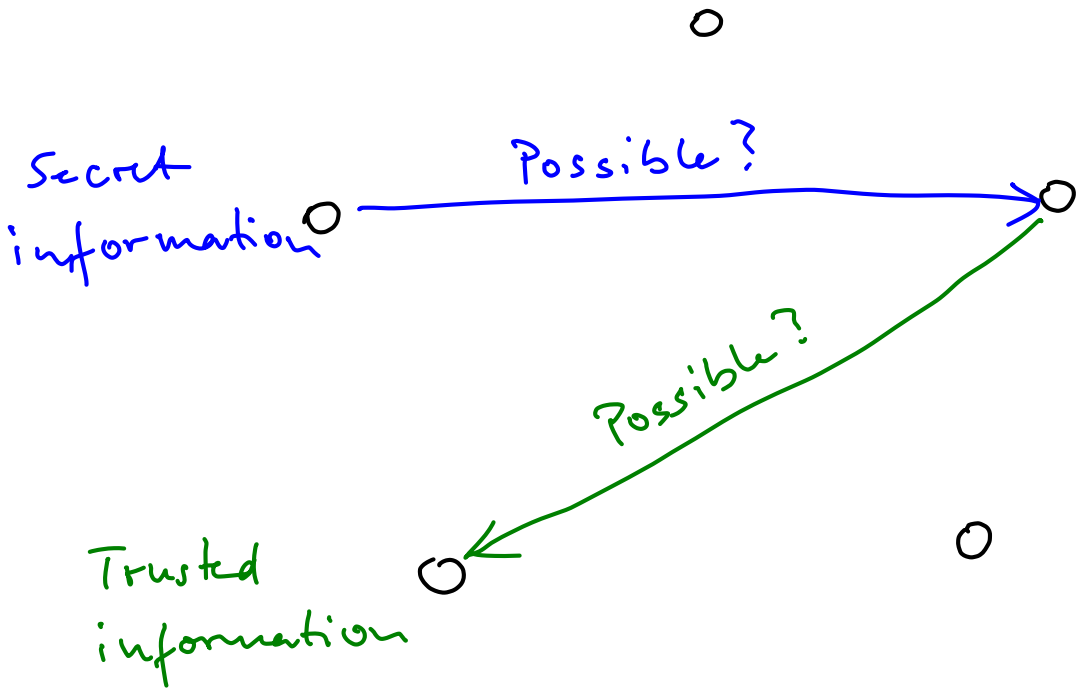
- **Goal of information flow analysis:**

  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

- ... "Places" in program that hold data



Confidentiality

Integrity

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

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

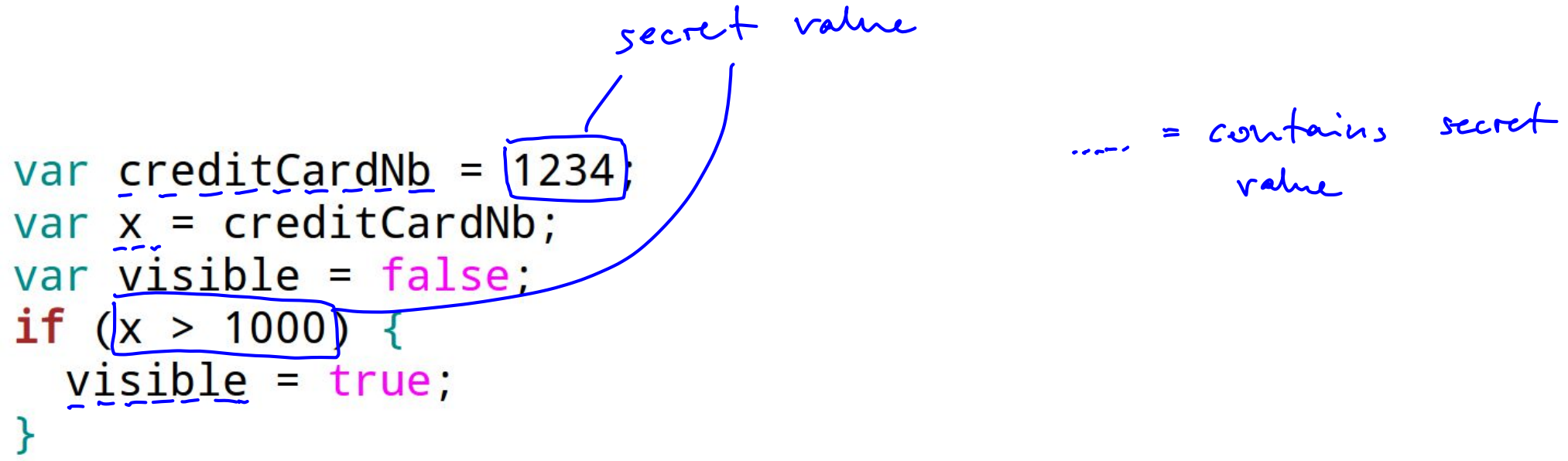
(Focus of this lecture: Confidentiality)

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

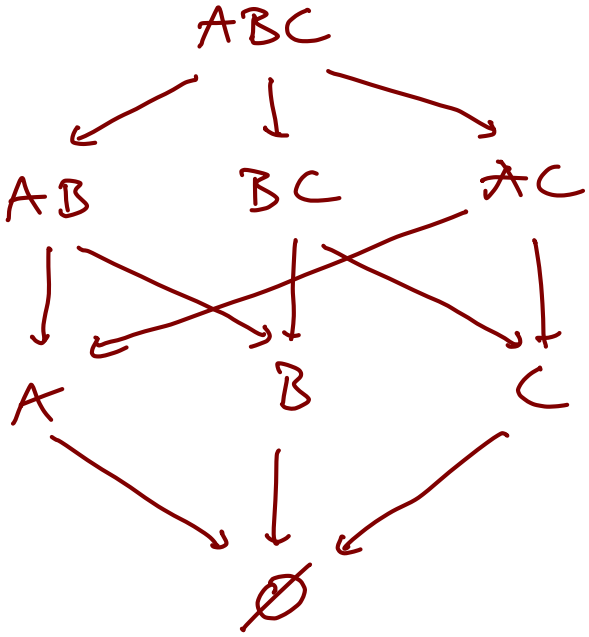
How to represent different levels of secrecy?

- **Set of security labels**
- **Form a universally bounded lattice**

Lattice: Examples

High → Low

Top Secret → Secret → Confidential → Public



(Arrows connect more secret class with less secret class.)

Universally Bounded Lattice

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

where:

S .. set of security classes

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

$\rightarrow$ .. partial order S (see figure)

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

$\top$ .. upper bound : ABC

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

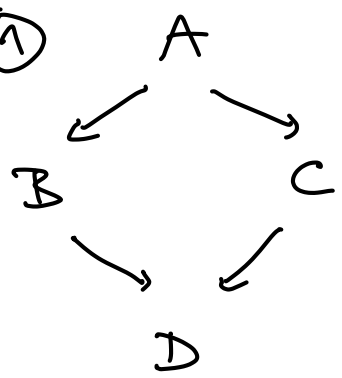
("combine two pieces of information")

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

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

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

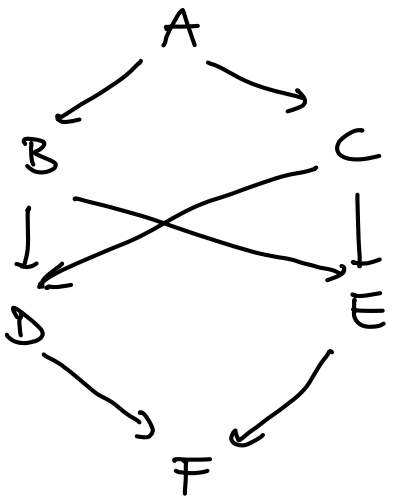
Quiz: Which of the following is a univ. bounded lattice?

① 

✓

② 

✓

③ 

$D \oplus E = ?$

three common upper bounds (B, C, A), but none is the least upper bound

④ 

no upper bound (infinite)

Flow Relation

- Partial order on security classes defines a flow relation
- Program is secure if and only if all information flows are described by the flow relation
- Intuition: No flow from higher to lower security class

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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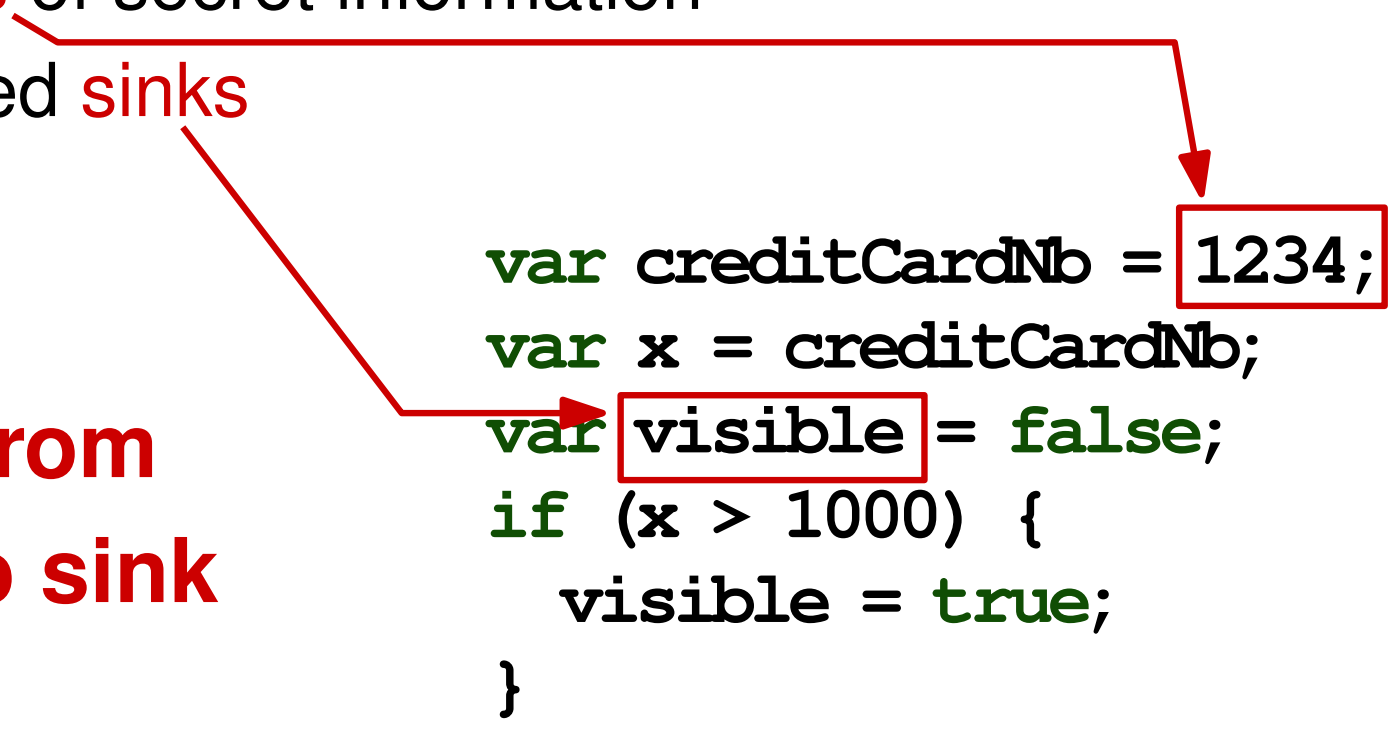

Goal:

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 subsequence statements

  But: This is intended

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

Declassification

- ”No flow from high to low” is impractical
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```
var password = ..  // secret
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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

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Explicit vs. Implicit Flows

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

```
var creditCardNb = 1234;
var x = creditCardNb;
var visible = false;
if (x > 1000) {
  visible = true;
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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**
- **Implicit flows**: **Caused by control flow dependence**

Some analyses consider only these

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

Explicit flow from `creditCardNb` to `x`

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

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

- **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

Focus of rest of this lecture

Taint Sources and Sinks

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

Taint Sources and Sinks

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  - Parameters given to a particular function
  - 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 where 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:

$$label(result) \leftarrow label(inp_1) \oplus ... \oplus label(inp_2)$$

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 the S is non-empty, consider all labels on S as input to the operation

Example 1

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

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

label (creditCard Nb) = secret

explicit flow: label (x) = secret

label (visible) = public

produce intermediate value b,
label (b) = label (x) ⊕ label (1000)
= secret ⊕ public = secret

push secret on S

labels on S are part of input
label (visible) = secret ⊕ label (true)
= 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?