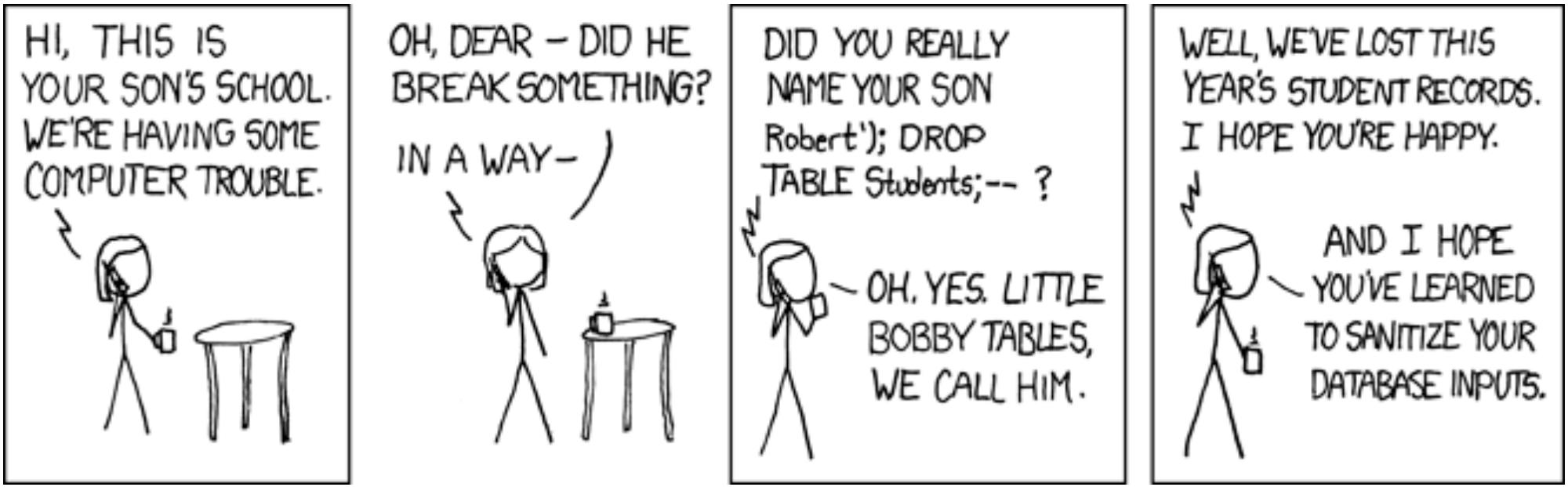


# TAINTED FLOW ANALYSIS

PROGRAM ANALYSIS AND OPTIMIZATION – DCC888

Fernando Magno Quintão Pereira
fernando@dcc.ufmg.br

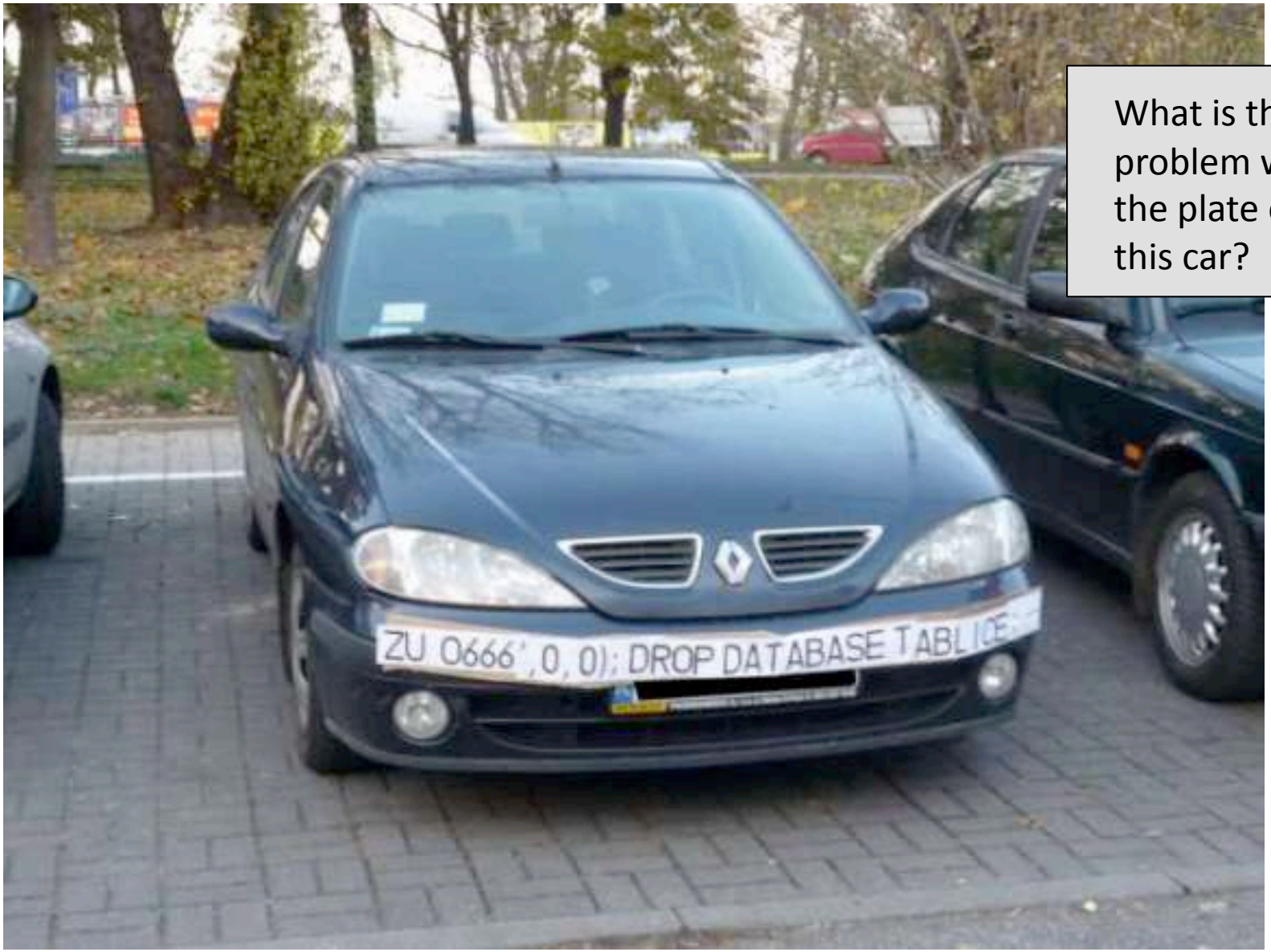
# An Example is Worth Many Words




1) What is the person behind the phone complaining about?

2) Have you ever seen such a problem before?

# Bobby Tables has got a Car




What is the problem with the plate of this car?

PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Information Flow

- Programs manipulate information.
- Some information should not leave the program.
  - Example: an uncriptographed password.
- Other information should not reach sensitive parts of the program.
  - Example: a string too large to fit into an array.

In the cartoon we just saw, what is the problem: information entering the program, or information leaving the program?

PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Information flow vulnerabilities

- If the user can read sensitive information from the program, we say that the program has an *information disclosure vulnerability*.
- If the user can send harmful information to the program, we say that the program has a *tainted flow vulnerability*.

1) Which tainted flow vulnerabilities can you think about?

2) Can you think about information disclosure vulnerabilities?

3) Can you think about a way to find out if a program has such a vulnerability. Try to be creative!

PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Tainted Flow Vulnerabilities

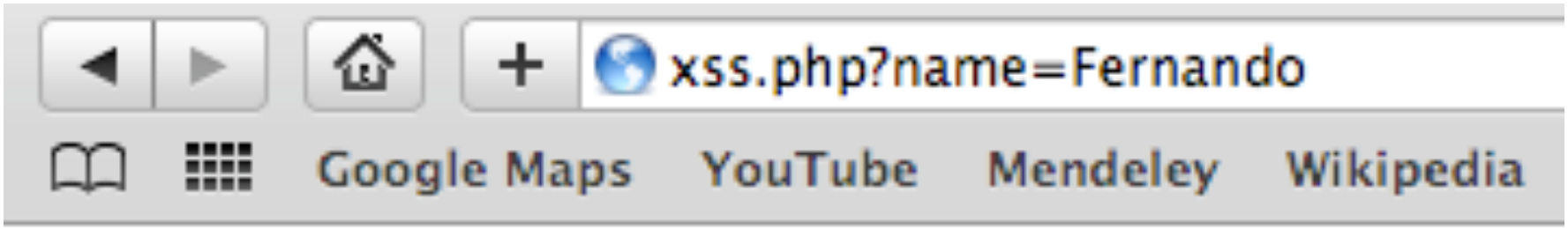
- An adversary can compromise the program by sending malicious information to it.
  - This type of attack is very common in web servers.

# An example of security bug

```
1   <?php
2     init_session();
3     echo “Hello ” . $_GET[‘name’];
4   ?>
```

What is the vulnerability of this program?

http://localhost/xss.php?name=Fernando



# An example of security bug

```
1   <?php
2     init_session();
3     echo “Hello ” . $_GET[‘name’];
4   ?>
```

http://localhost/xss.php?name=Fernando

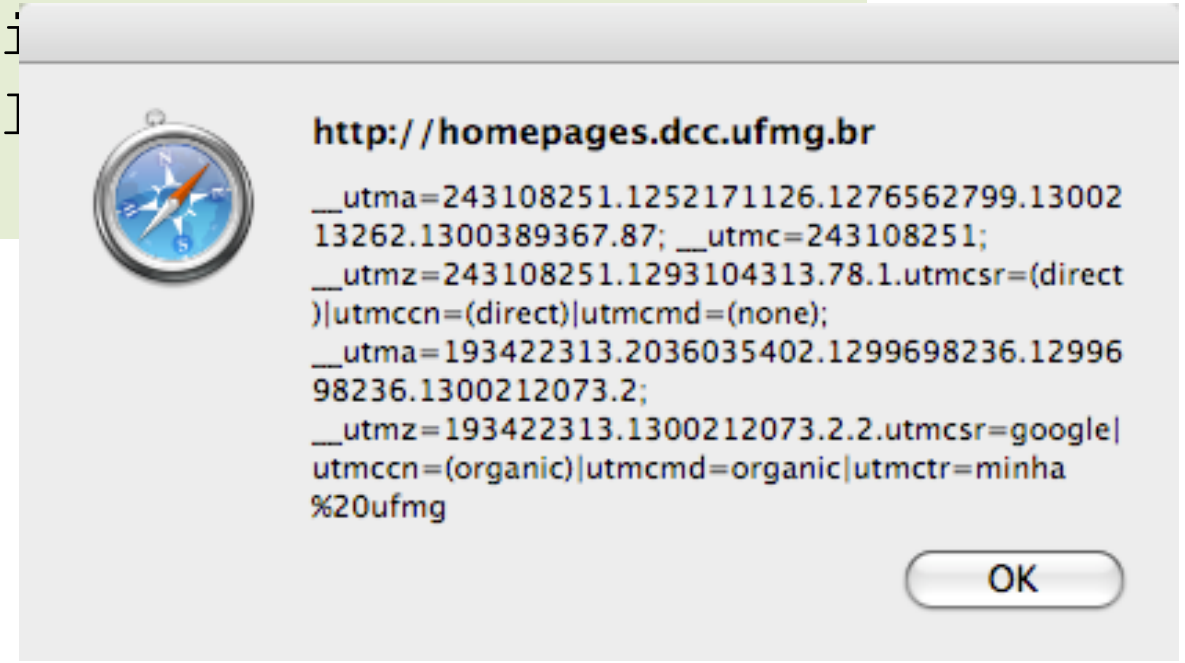
Hello Fernando

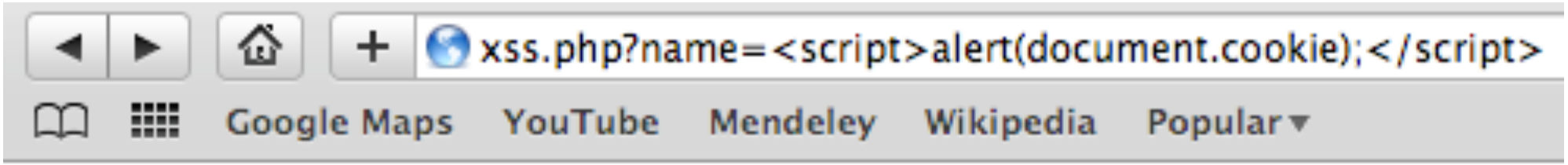
**How to steal a cookie:**

```
http://localhost/xss.php?
name=<script>alert(docume
nt.cookie);</script>
```

# An example of security bug

```
1   <?php
2     init_sessi
3     echo "Hell
4   ?>
```




Hello

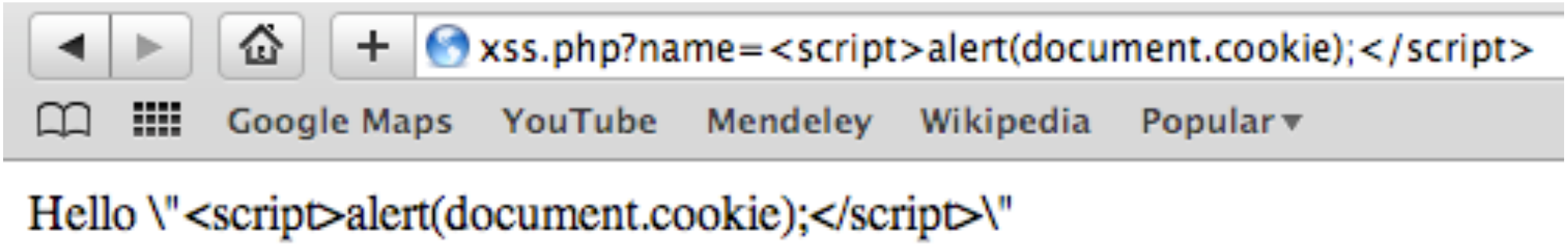
# An example of security bug

```
1   <?php
2     init_session();
3     echo “Hello ” . $_GET[‘name’];
4   ?>
```

How to clean this program?

# An example of security bug


```
1   <?php
2     init_session();
3     echo “Hello ” .
        htmlentities($_GET[‘name’]);
4   ?>
```



# There are several ways to break a program

```
$id = $_GET[”user”];

if ($id == '') {
  echo "Invalid user: $id"
} else {
  $getuser = $DB->query
      (”SELECT * FROM `table` WHERE id=’$id’”);
  echo $getuser;
}
```

What is the vulnerability of this program?

# There are several ways to break a program

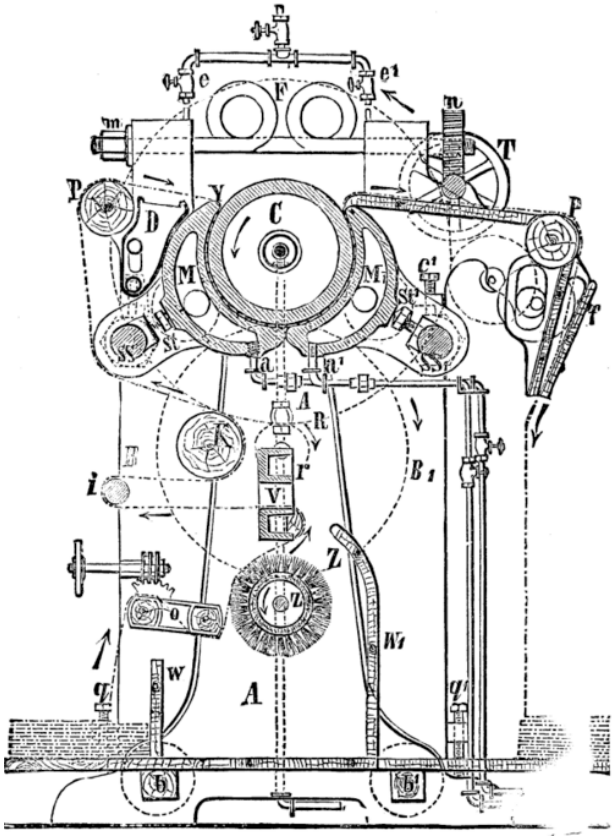
```
$id = $_GET[”user”];

if ($id == '') {
  echo "Invalid user: $id"
} else {
  $getuser = $DB->query
      (”SELECT * FROM `table` WHERE id=’$id’”);
  echo $getuser;
}
```

What if the name of the student is `Robert’); drop table Students ; --`

# The Tainted Flow Problem

- Instance: a tuple T = (**P**, SO, SI, SA)
  - **P → Program**
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers



```
<?php
  echo htmlentities($_GET['name']);
?>
```

# The Tainted Flow Problem

- Instance: a tuple T = (P, **SO**, SI, SA)
  - P → Program
  - **SO → Sources**
  - SI → Sinks
  - SA → Sanitizers

```
<?php
  echo htmlentities($_GET['name']);
?>
```

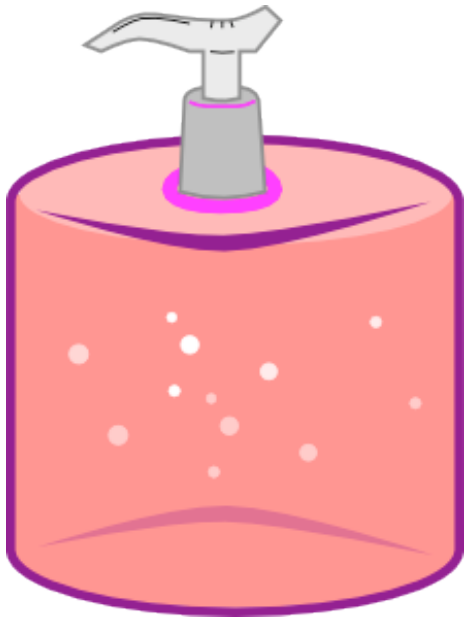
# The Tainted Flow Problem

- Instance: a tuple T = (P, SO, **SI**, SA)
  - P → Program
  - SO → Sources
  - **SI → Sinks**
  - SA → Sanitizers

```
<?php
  echo htmlentities($_GET['name']);
?>
```

# The Tainted Flow Problem

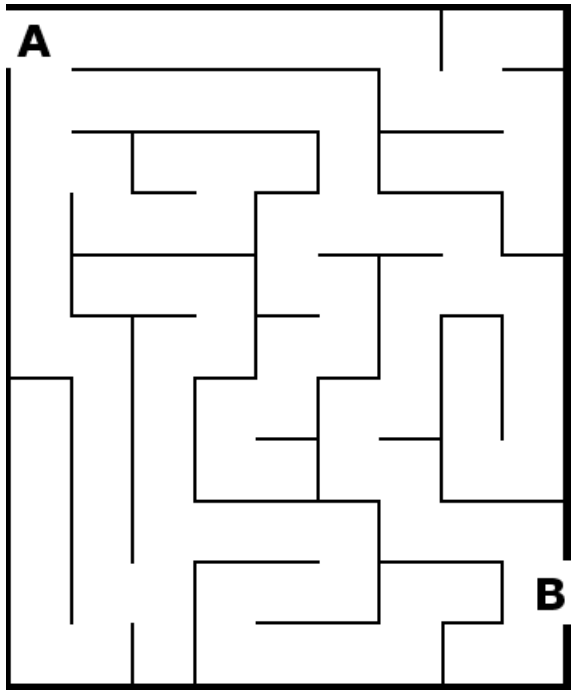
- Instance: a tuple T = (P, SO, SI, **SA**)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - **SA → Sanitizers**



```
<?php
  echo htmlentities($_GET['name']);
?>
```

# The Tainted Flow Problem

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers
- Problem: find a path from a source to a sink that does not go across a sanitizer




What do you think I mean by path?

# Example: cross-site scripting (XSS)

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers

**Cross-site Scripting (XSS)**

**SO:** `$_GET, $_POST, ...`

**SI:** `echo, print, printf, ...`

**SA:** `htmlentities, strip_tags,...`

# Example: XSS


```
<?php
  $name = $_GET['name'];
  echo $name;
?>
```

```
<?php
  $name = htmlentities($_GET['name']);
  echo $name;
?>
```

# Example: SQL injection

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers

**SQL injection:**

**SO:** `$_GET, $_POST, ...`

**SI:** `mysql_query, pg_query, ...`

**SA:** `addslashes, pg_escape_string,...`

# Example: SQL Injection


```
<?php
  $userid = $_GET['userid'];
  $passwd = $_GET['passwd'];
  ...
  $result = mysql_query("SELECT userid FROM users
     WHERE userid=$userid AND
passwd='$passwd'");
?>
```

Can you find a **string** that goes around the password guard?

```
<?php
  $userid = (int) $_GET['userid'];
  $passwd = addslashes($_GET['passwd']);
  ...
  $result = mysql_query("SELECT userid FROM
     users WHERE userid=$userid AND
     passwd='$passwd'");
?>
```

# Example: Command Execution

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers

**Command Execution:**

**SO:** `$_GET, $_POST, ...`

**SI:** `exec, system, passthru, ...`

**SA:** `escapeshellcmd, escapeshellarg,..`

# Example: Command Execution


```
<?php
  $filename = $_GET['filename'];
  system("/usr/bin/file $filename");
?>
```

1) Do you know what the `file` command does?

2) Can you do anything evil with **this** program?

```
<?php
  $filename = escapecmdshell
    ($_GET['filename']);
  system("/usr/bin/file $filename");
?>
```

# Example: Remote File Inclusion

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers

**Remote File Inclusion:**

**SO:** `$_GET, $_POST, ...`

**SI:** `include, include_once, require, require_once, ...`

**SA:** ?

# Example: Remote File Inclusion


```
<?php
  $file = $_GET['filename'];
  include($file);
?>
```

```
<?php
  $file_incs = array("file1", ..., "fileN");
  $file_id = $_GET['file_id'];

  $inc = $file_incs[$file_id];
  if (isset($inc))
    include($inc);
  else
    echo "Error...";
?>
```

# Example: File System Access

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers

**File System Access:**

**SO:** `$_GET, $_POST, ...`

**SI:** `chdir, mkdir, rmdir, rename, copy, chgrp, chown, chmod, unlink, ...`

**SA:** ?

# Example: File System Access


```
<?php
  $filename = $_GET['filename'];
  unlink($filename);
?>
```

The developer can use the same methods used to guard against remote file inclusion attacks.

# Example: Malicious Evaluation

- Instance: a tuple T = (P, SO, SI, SA)
  - P → Program
  - SO → Sources
  - SI → Sinks
  - SA → Sanitizers

**Malicious Evaluation:**

**SO:** `$_GET, $_POST, ...`

**SI:** `eval, preg_replace, ...`

**SA:** ?

# Example: Malicious Evaluation


```
<?php
  $code = $_GET['code'];
  eval($code);
?>
```

There is not a systematic way of checking statically that dynamic code is safe…

# It is a serious problem...

- The Annual SANS's Report estimates that SQL injection attacks have happened 19 million times in July 2009.

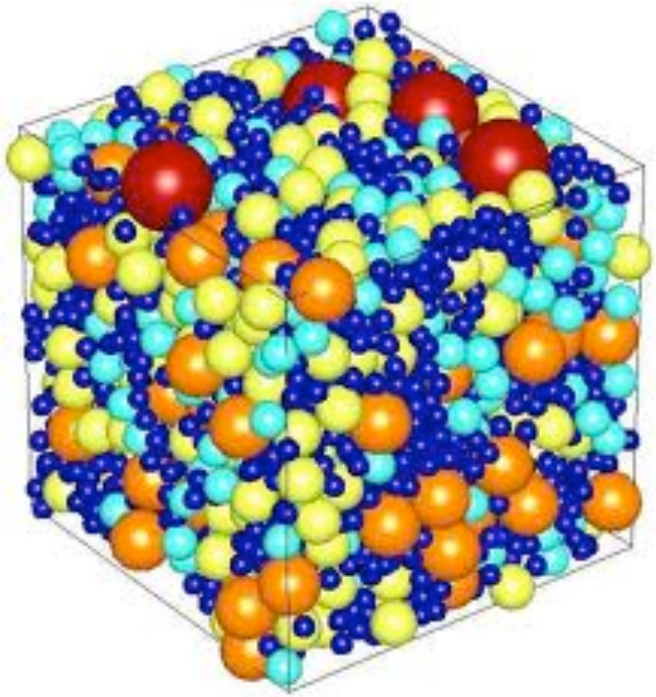
- CVE[1] 2006 statistics:
  - #1: Cross-site scripting: 18.5%
  - #2: SQL injection: 13.6%
  - #3: remote file inclusion: 13.1%
  - #17: command execution: 0.4%
  - #24: Eval injection: 0.3%

[1]: Common Vulnerabilities and Exposures

# Discovering Tainted Flow Vulnerabilities

- How can we find if a program contains a tainted flow vulnerability?
  - Is your algorithm decidable?
  - Is it fast?
  - Is it too **conservative**? In other words, can it output a false positive?
  - Is it **sound**? In other words, can it produce false negatives?
  - Does it work for every kind of tainted flow vulnerability?

# DENSE TAINTED FLOW ANALYSIS

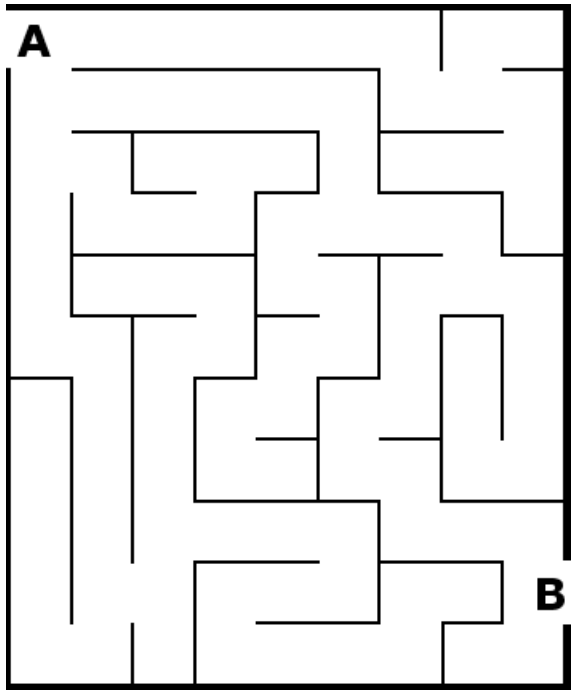


DCC 888

# How to detect tainted flow vulnerabilities?

- Problem: find a path from a source to a sink that does not go across a sanitizer.

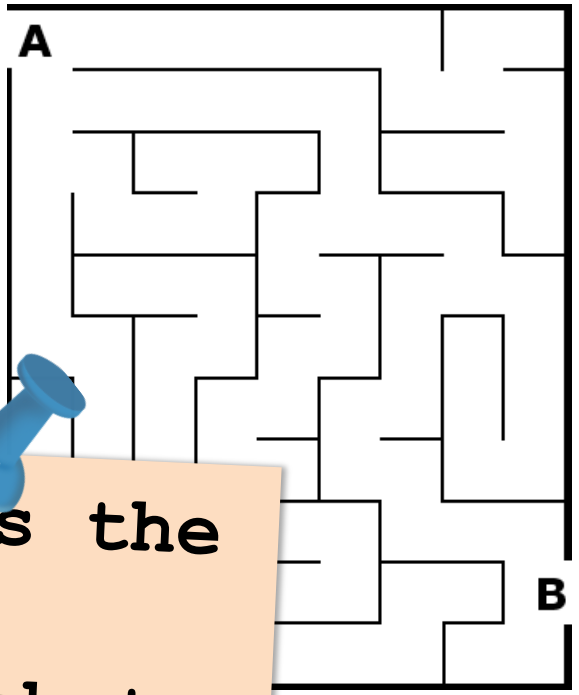
The very old question: what is a path inside the program?



# How to detect tainted flow vulnerabilities?

- Problem: find a path from a source to a sink that does not go across a sanitizer.

The very old question: what is a path inside the program?




**A path is a chain of data dependences in a program**

**A path is the flow of control that exists in the program**

PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Nano-PHP: our toy language

- Often it is useful to define a static analysis on a small programming language.
- We can prove properties for this programming language.
- These proofs not only enhance confidence on the algorithm, but they also help the reader to understand how the algorithm works.
- The toy language should be simple, so that the entire exposition of ideas is not complex.
- Yet, it should be complex enough to include every aspect of the algorithm that will be important in the real world.

# Nano-PHP: our toy language

| Name | Instruction | Example |
|---|---|---|
| **Assignment from source** | **v = ❍** | **`$x = $_POST['content']`** |
| Assignment to sink | ● = v | `echo($v)` |
| Simple assignment | x = ⊗($x_1$, …, $x_n$) | `$a = $t1 * $t2` |
| Branch | bra $l_1$, …, $l_n$ | `if (…) {…} else {…}` |
| Filter | x = filter | `$a = htmlentities($t1)` |
| Validator | validate x, $l_c$, $l_t$ | `if(is_num($t1)) {…}` |

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

$l_0$: v = ❍
$l_1$: x = filter
$l_2$: validate(v, $l_3$, $l_9$)
$l_3$: bra $l_4$, $l_8$
$l_4$: ● = x
$l_5$: v = ❍
$l_6$: v = ⊗(v)
$l_7$: bra $l_4$
$l_8$: ● = x
$l_9$: bra $l_4$

# Nano-PHP: our toy language

| Name | Instruction | Example |
|---|---|---|
| Assignment from source | v = ❍ | `$x = $_POST['content']` |
| Assignment to sink | ● = v | `echo($v)` |
| Simple assignment | x = ⊗($x_1$, …, $x_n$) | `$a = $t1 * $t2` |
| Branch | bra $l_1$, …, $l_n$ | `if (…) {…} else {…}` |
| **Filter** | **x = filter** | **`$a = htmlentities($t1)`** |
| Validator | validate x, $l_c$, $l_t$ | `if(is_num($t1)) {…}` |

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

$l_0$: v = ❍
$l_1$: x = filter
$l_2$: validate(v, $l_3$, $l_9$)
$l_3$: bra $l_4$, $l_8$
$l_4$: ● = x
$l_5$: v = ❍
$l_6$: v = ⊗(v)
$l_7$: bra $l_3$
$l_8$: ● = x
$l_9$: bra $l_9$

# Nano-PHP: our toy language

| Name | Instruction | Example |
|---|---|---|
| Assignment from source | v = ❍ | `$x = $_POST['content']` |
| Assignment to sink | ● = v | `echo($v)` |
| Simple assignment | x = ⊗($x_1$, …, $x_n$) | `$a = $t1 * $t2` |
| Branch | bra $l_1$, …, $l_n$ | `if (…) {…} else {…}` |
| Filter | x = filter | `$a = htmlentities($t1)` |
| **Validator** | **validate x, $l_c$, $l_t$** | **`if(is_num($t1)) {…}`** |

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

$l_0$: v = ❍
$l_1$: x = filter
**$l_2$: validate(v, $l_3$, $l_9$)**
$l_3$: bra $l_4$, $l_8$
$l_4$: ● = x
$l_5$: v = ❍
$l_6$: v = ⊗(v)
$l_7$: bra $l_3$
$l_8$: ● = x
$l_9$: bra $l_9$

# Nano-PHP: our toy language

| Name | Instruction | Example |
|---|---|---|
| Assignment from source | v = ❍ | `$x = $_POST['content']` |
| Assignment to sink | ● = v | `echo($v)` |
| Simple assignment | x = ⊗($x_1$, …, $x_n$) | `$a = $t1 * $t2` |
| **Branch** | **bra $l_1$, …, $l_n$** | **`if (…) {…} else {…}`** |
| Filter | x = filter | `$a = htmlentities($t1)` |
| Validator | validate x, $l_c$, $l_t$ | `if(is_num($t1)) {…}` |

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

$l_0$: v = ❍
$l_1$: x = filter
$l_2$: validate(v, $l_3$, $l_9$)
**$l_3$: bra $l_4$, $l_8$**
$l_4$: ● = x
$l_5$: v = ❍
$l_6$: v = ⊗(v)
$l_7$: bra $l_3$
$l_8$: ● = x
$l_9$: bra $l_9$

# Nano-PHP: our toy language

| Name | Instruction | Example |
|---|---|---|
| Assignment from source | v = ❍ | `$x = $_POST['content']` |
| **Assignment to sink** | **● = v** | **`echo ($v)`** |
| Simple assignment | x = ⊗($x_1$, …, $x_n$) | `$a = $t1 * $t2` |
| Branch | bra $l_1$, …, $l_n$ | `if (…) {…} else {…}` |
| Filter | x = filter | `$a = htmlentities($t1)` |
| Validator | validate x, $l_c$, $l_t$ | `if(is_num($t1)) {…}` |

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

$l_0$: v = ❍
$l_1$: x = filter
$l_2$: validate(v, $l_3$, $l_9$)
$l_3$: bra $l_4$, $l_8$
**$l_4$: ● = x**
$l_5$: v = ❍
$l_6$: v = ⊗(v)
$l_7$: bra $l_3$
$l_8$: ● = x
$l_9$: bra $l_9$

# Nano-PHP: our toy language

| Name | Instruction | Example |
|---|---|---|
| Assignment from source | v = ❍ | `$x = $_POST['content']` |
| Assignment to sink | ● = v | `echo($v)` |
| **Simple assignment** | **x = ⊗($x_1$, …, $x_n$)** | **`$a = $t1 * $t2`** |
| Branch | bra $l_1$, …, $l_n$ | `if (…) {…} else {…}` |
| Filter | x = filter | `$a = htmlentities($t1)` |
| Validator | validate x, $l_c$, $l_t$ | `if(is_num($t1)) {…}` |

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

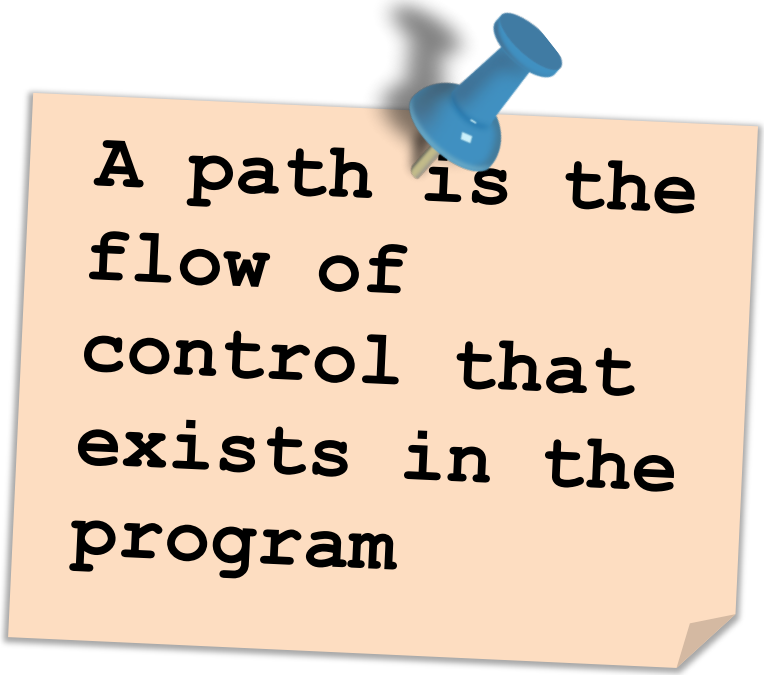
$l_0$: v = ❍
$l_1$: x = filter
$l_2$: validate(v, $l_3$, $l_9$)
$l_3$: bra $l_4$, $l_8$
$l_4$: ● = x
$l_5$: v = ❍
**$l_6$: v = ⊗(v)**
$l_7$: bra $l_3$
$l_8$: ● = v
$l_9$: bra $l_9$

# Path as Control Flow

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

1) Does this program contain a vulnerability?

2) What is the control flow graph of this program?

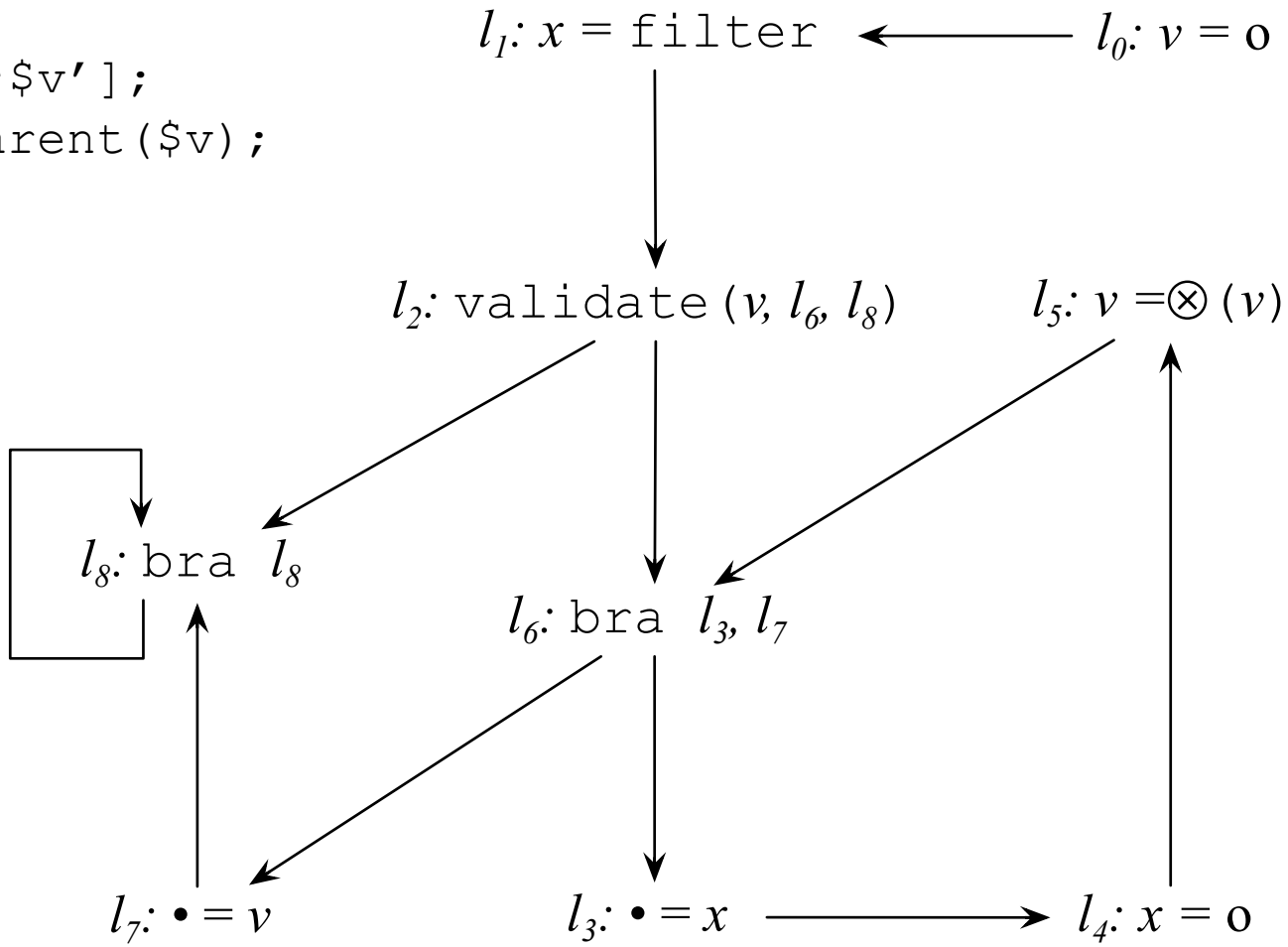


# Path as Control Flow

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

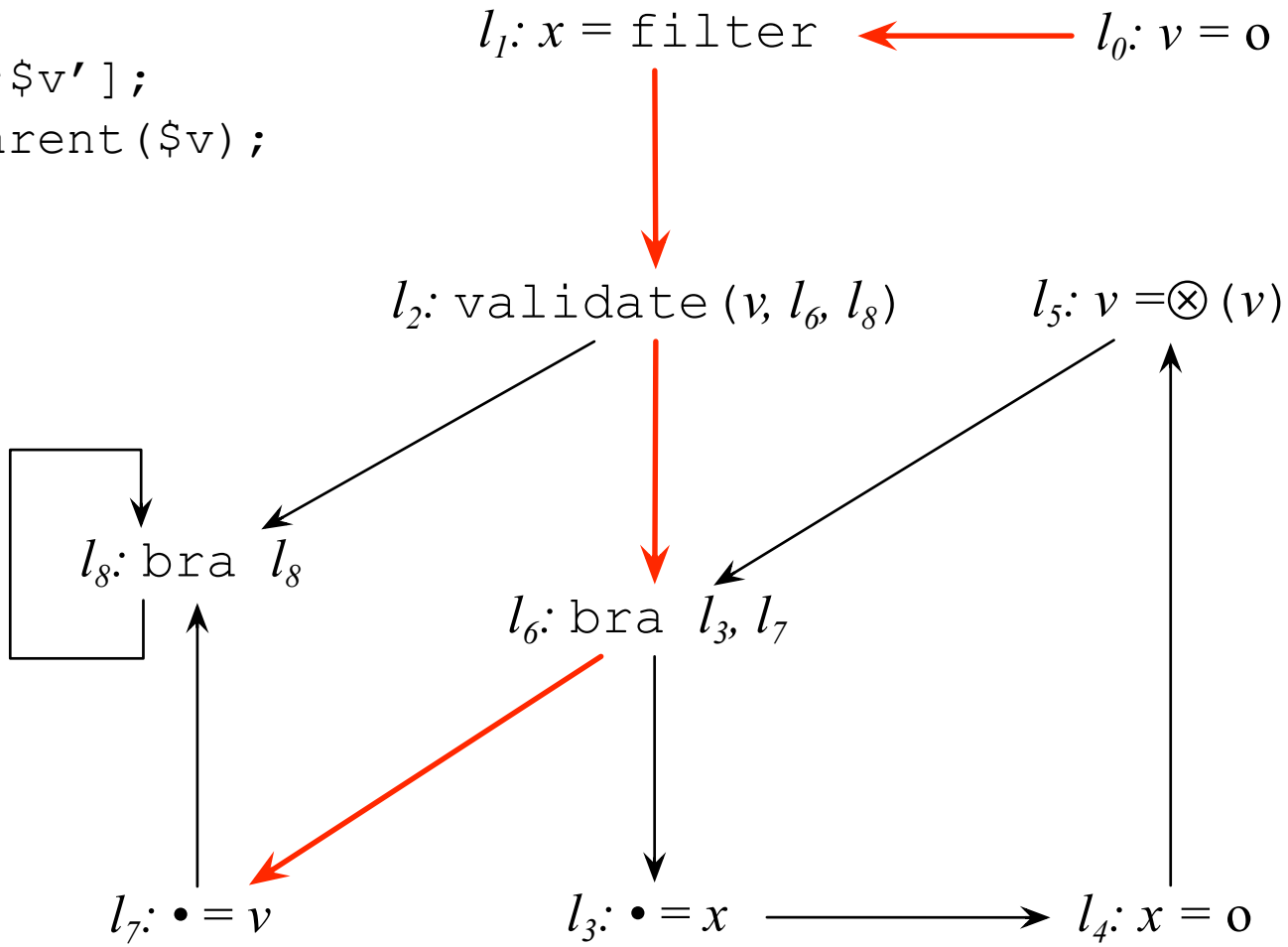
Can you find a vulnerable path along the control flow graph of this program?

$l_0$: v = ❍
$l_1$: x = filter
$l_2$: validate(v, $l_3$, $l_9$)
$l_6$: bra $l_3$, $l_7$
$l_3$: ● = x
$l_4$: x = ❍
$l_5$: v = ⊗(v)
$l_7$: ● = v
$l_8$: bra $l_8$



# Path as Control Flow

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```



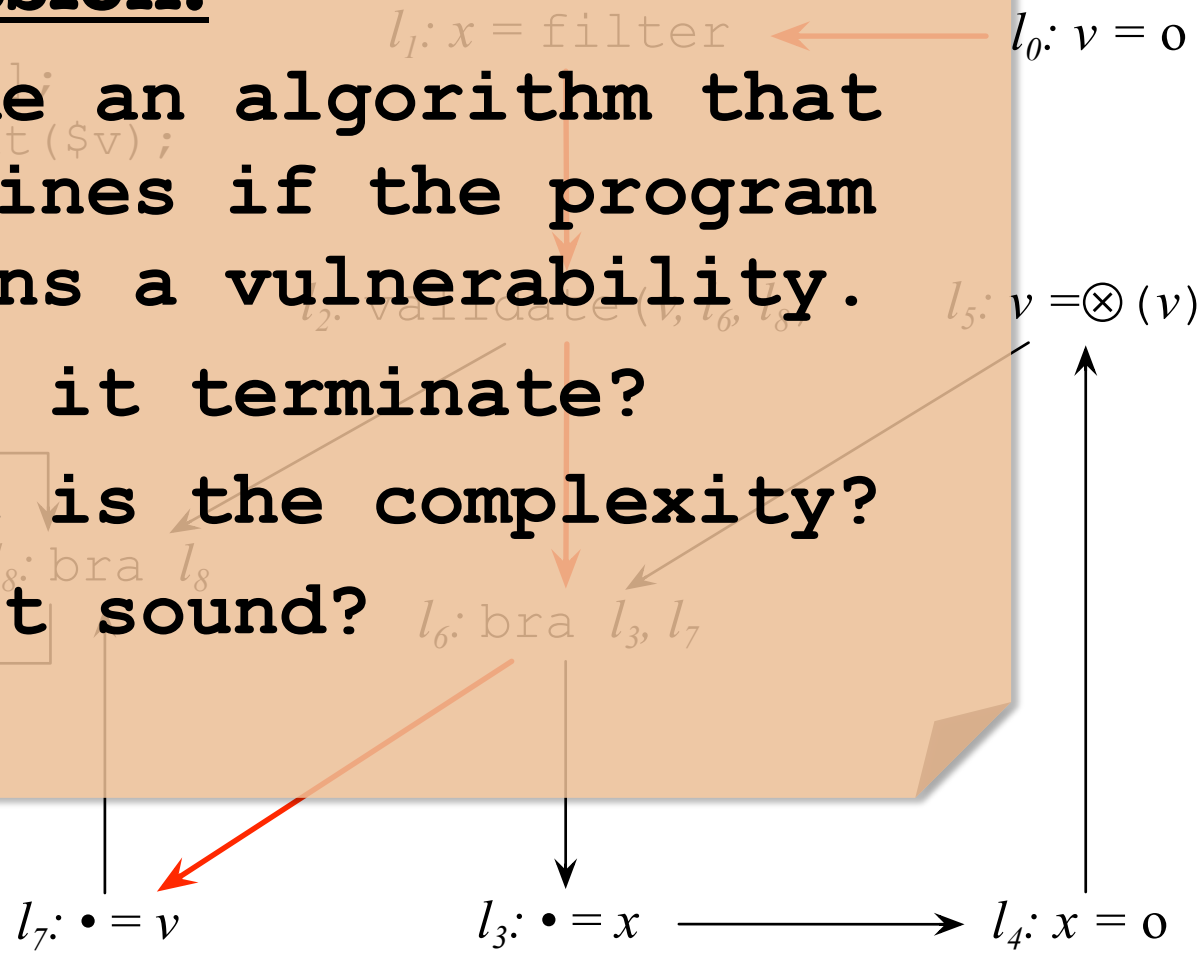
# Tracking the Program Data Flow

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['val'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

**The mission:**

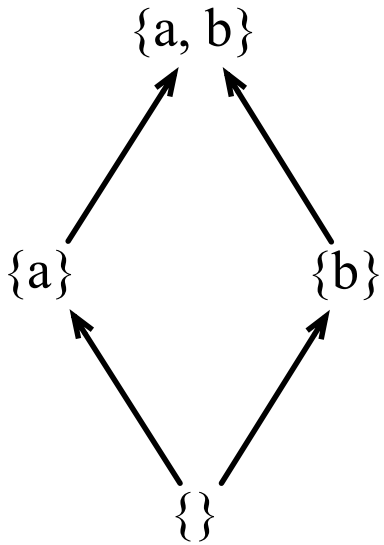
**Provide an algorithm that determines if the program contains a vulnerability.**

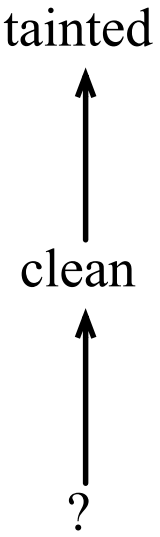
* **Does it terminate?**
* **What is the complexity?**
* **Is it sound?**



# Data Flow Analysis

- A program point is any point between two consecutive instructions.
- Lets associate with each program point a function that maps variables to either clean or tainted.
- This function is, indeed, a point in the product lattice of the two lattices below, assuming two variables, a and b:

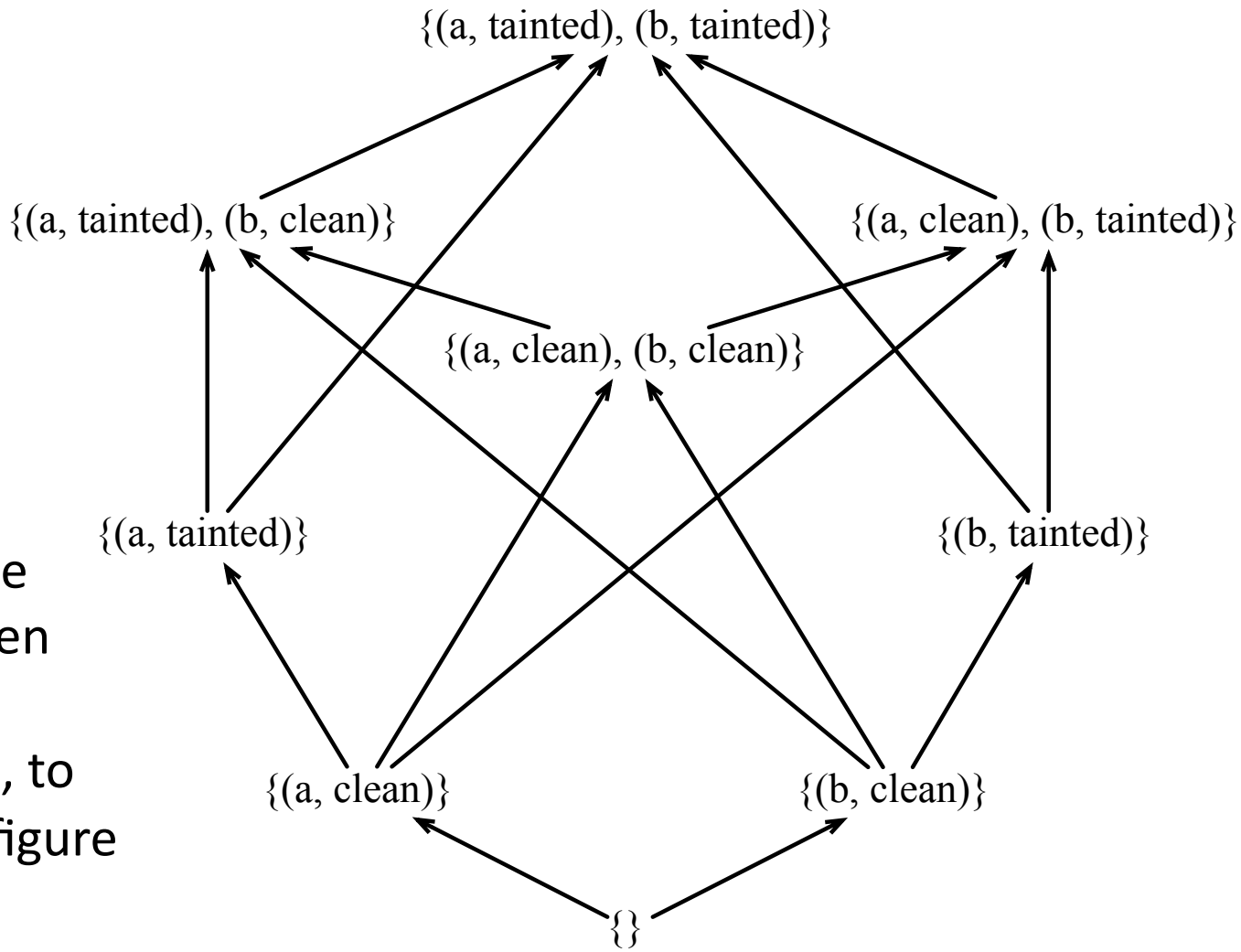



Which lattice do we obtain from the product of these two lattices?

# Data Flow Analysis

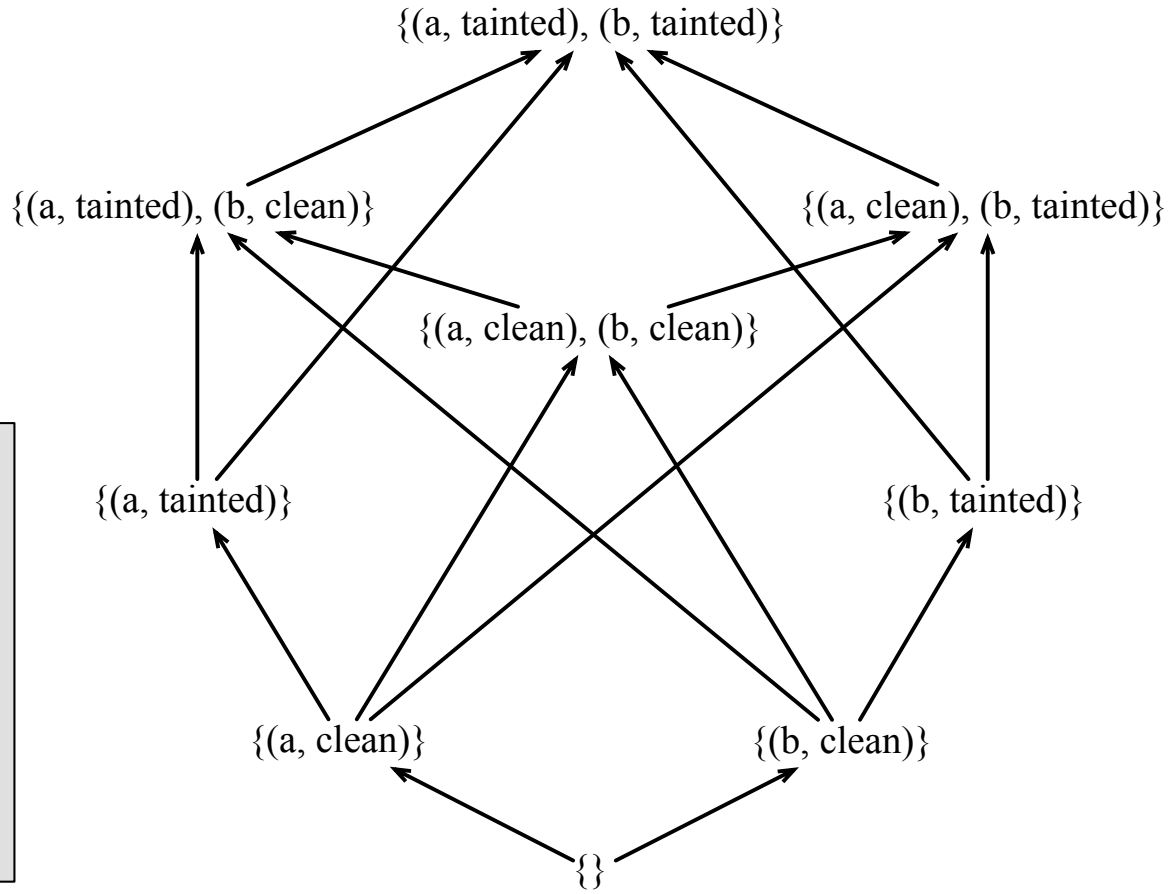
- We will use this product lattice, whose diagram is seen below:




We did not draw the associations between variables and the undefined value (?), to avoid clogging the figure too much.

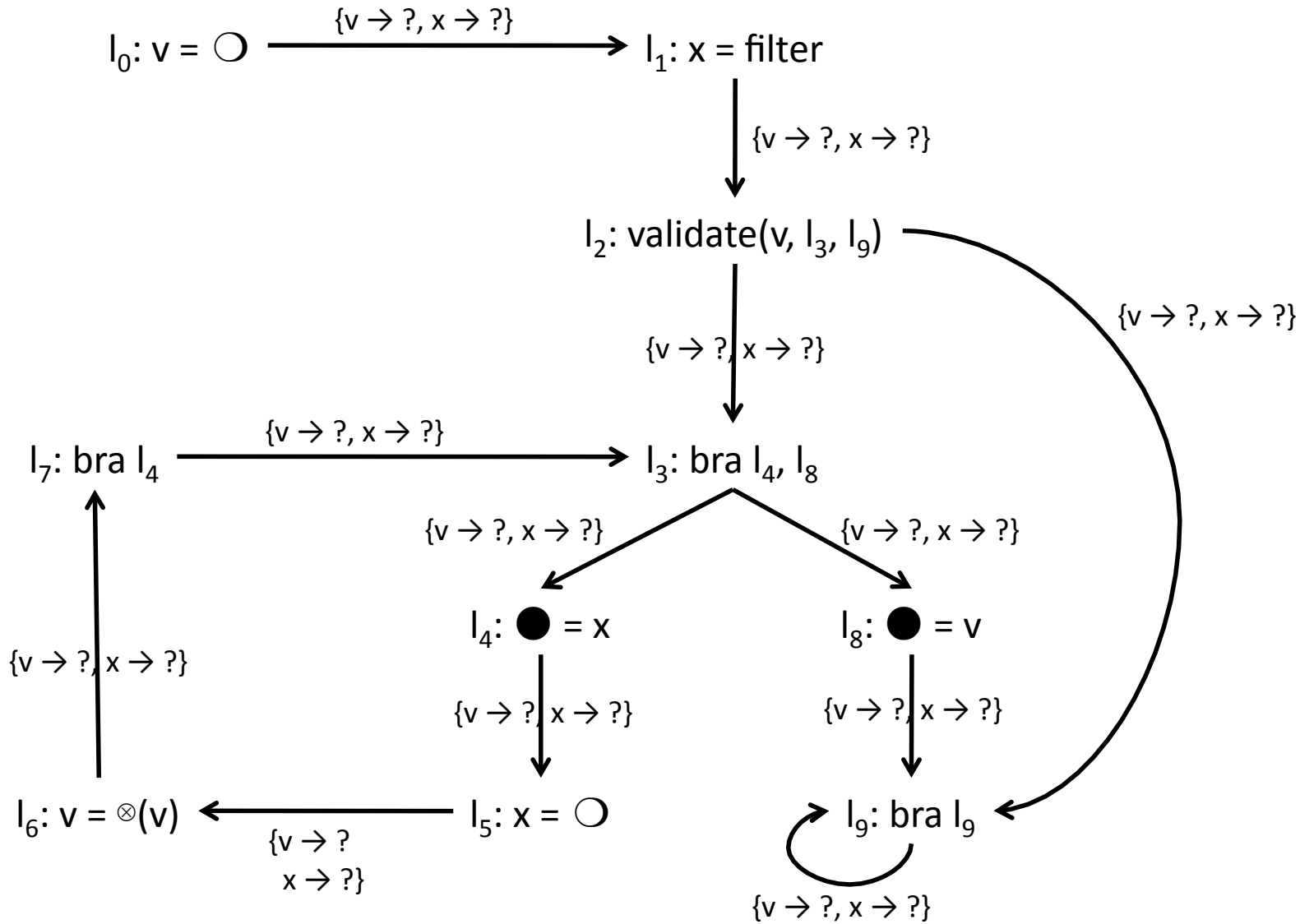
# Dense Data Flow Analysis

- Notice that our analysis will be *dense*:
  - We are associating each pair (p, v) with an abstract state, where p is a program point, and v is a variable.

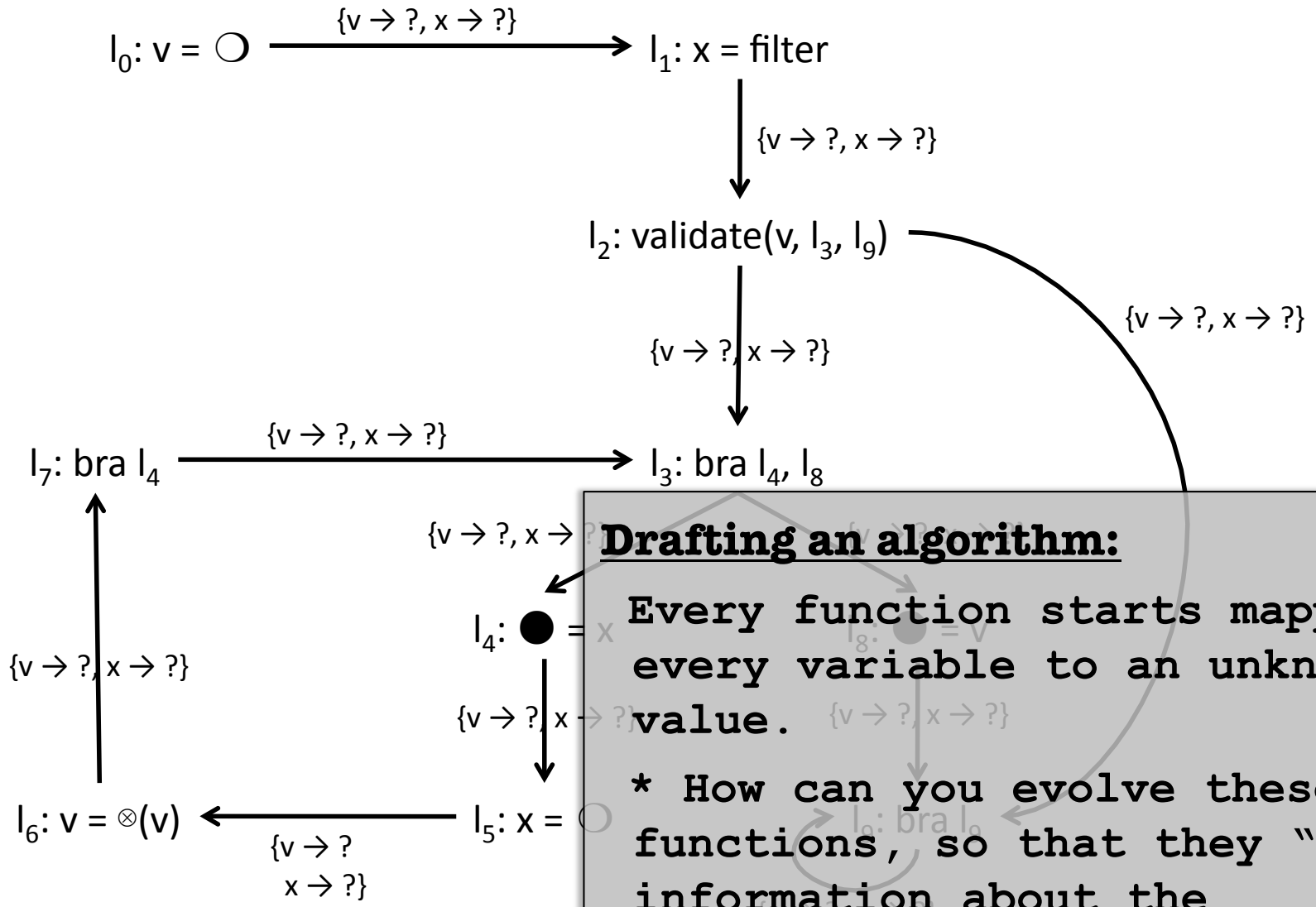



So, given a program with V variables, and P points, how many iterations we will need, in the worst case, to determine the abstract state of all the pairs (vars × points)?

# Example of dense approach



# Example of dense approach

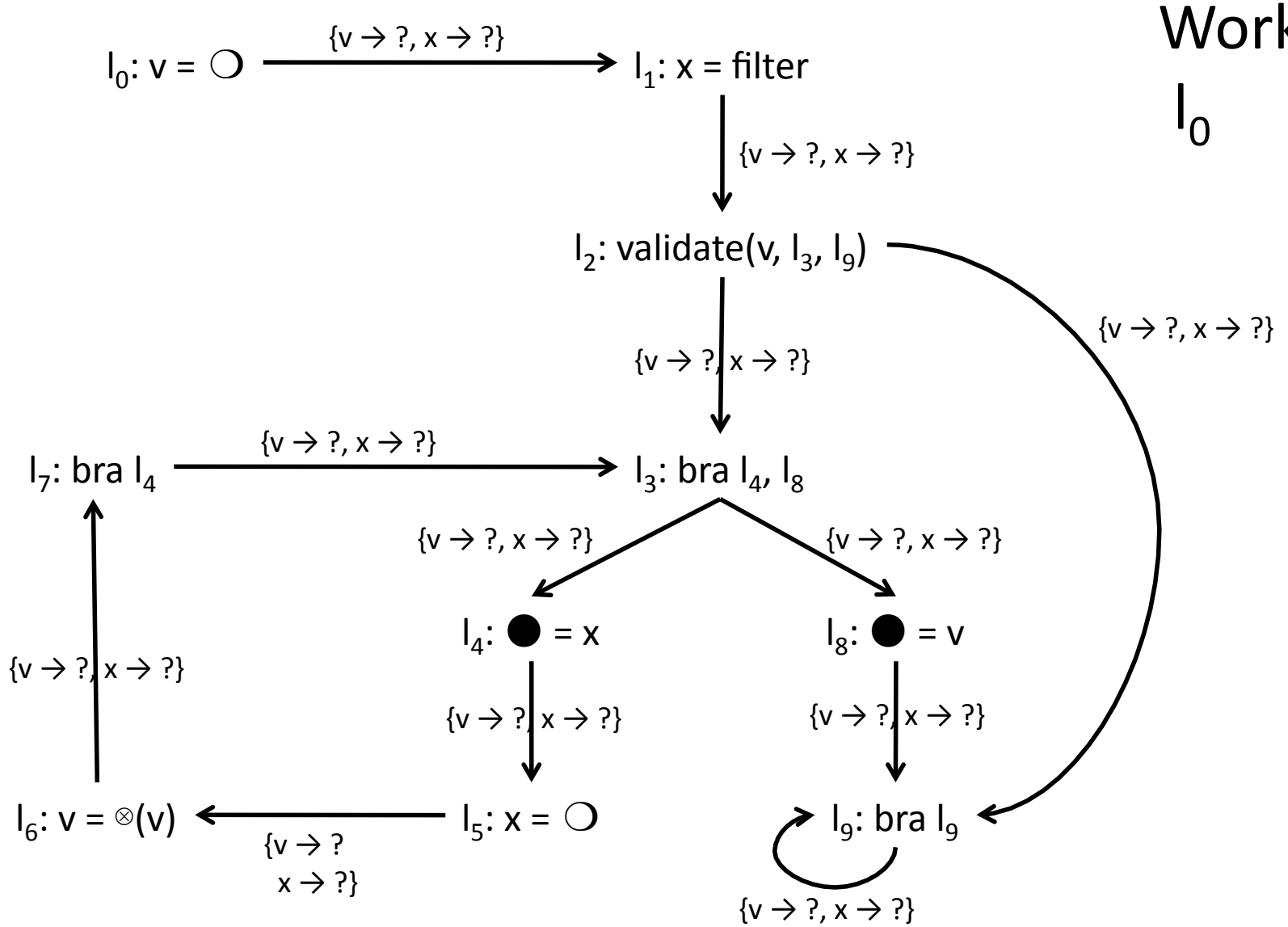



**Drafting an algorithm:**

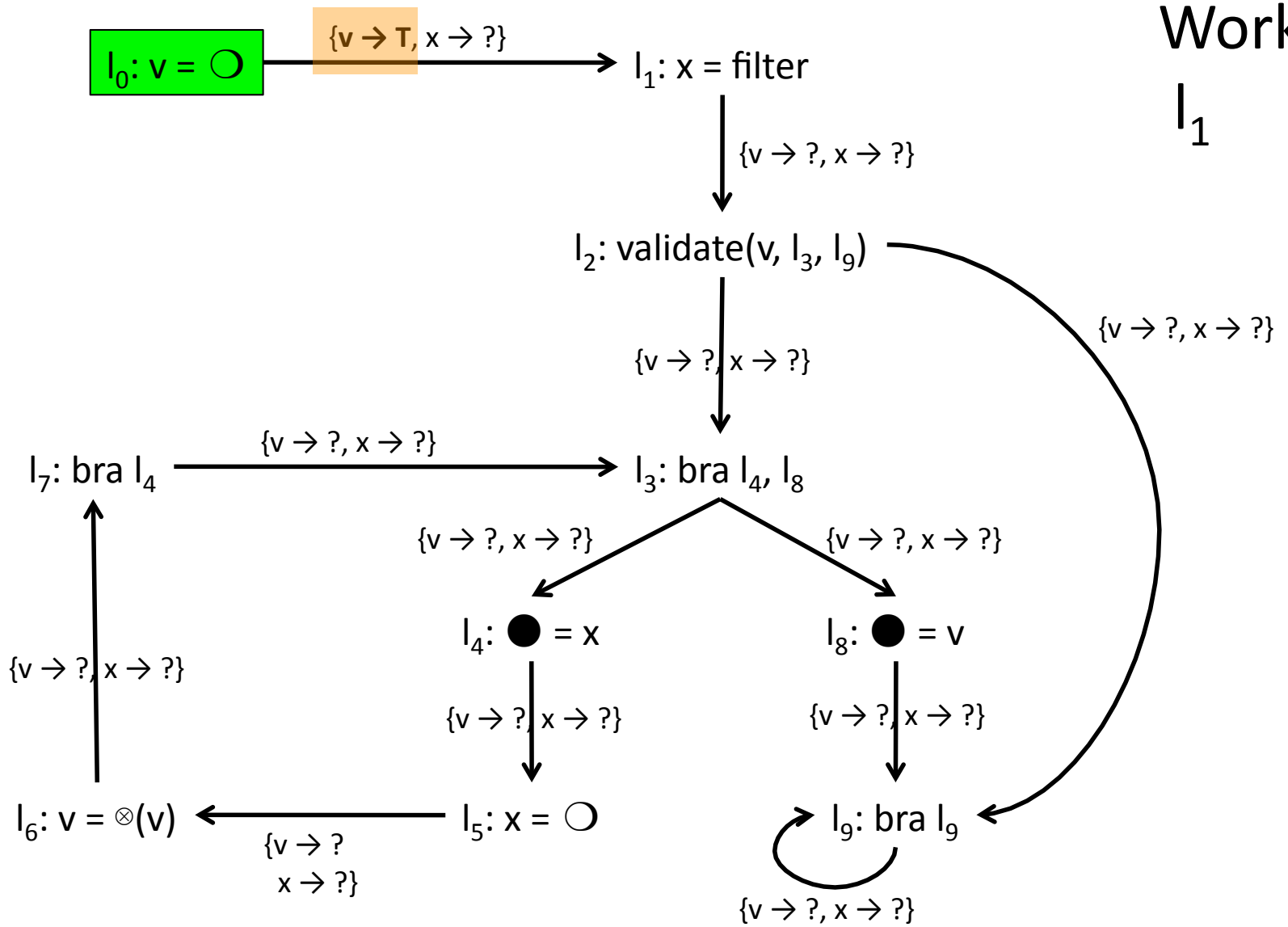
**Every function starts mapping every variable to an unknown value.**

*** How can you evolve these functions, so that they "learn" information about the variables?**

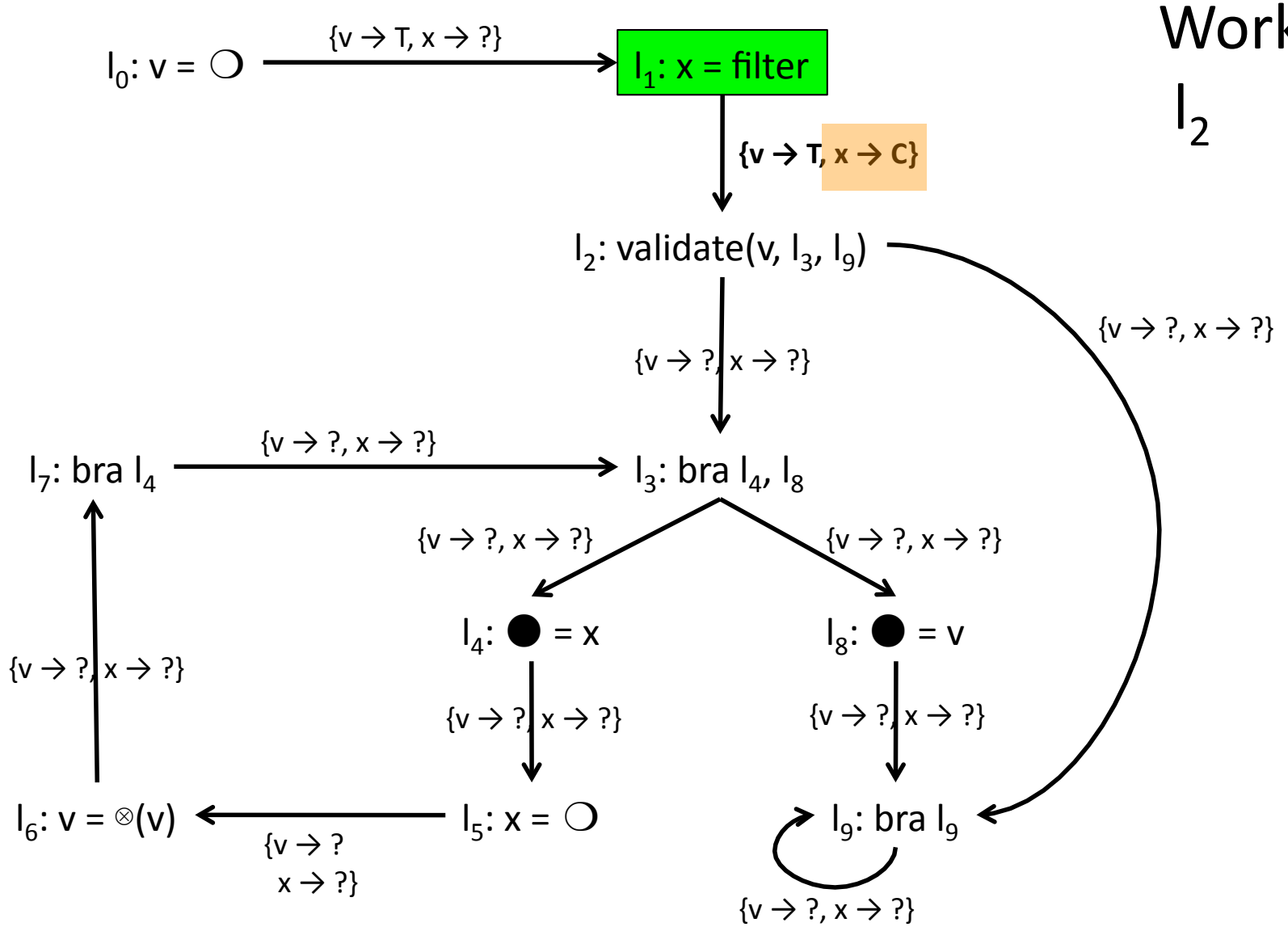
# Example of dense approach



# Example of dense approach



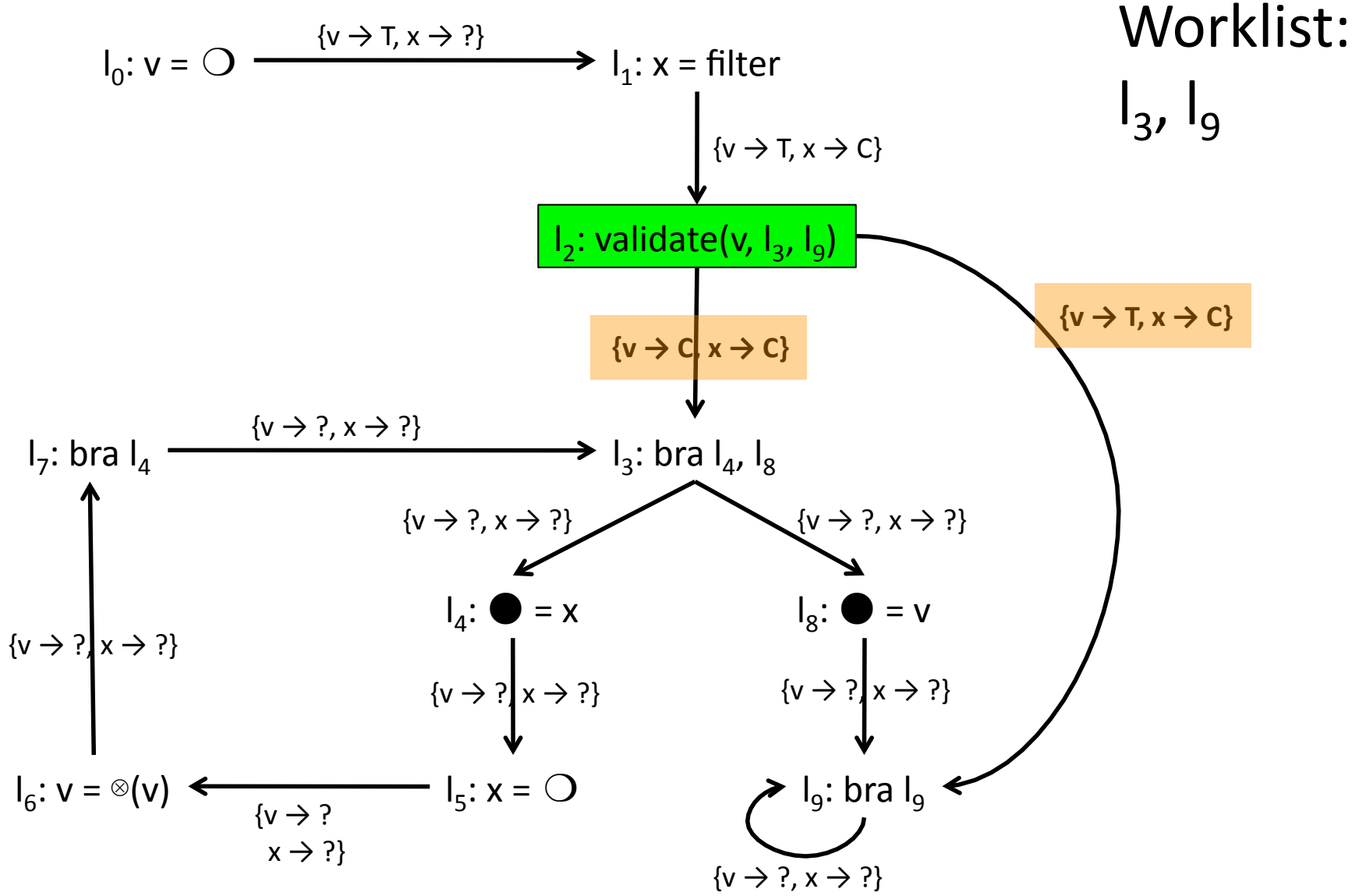
# Example of dense approach



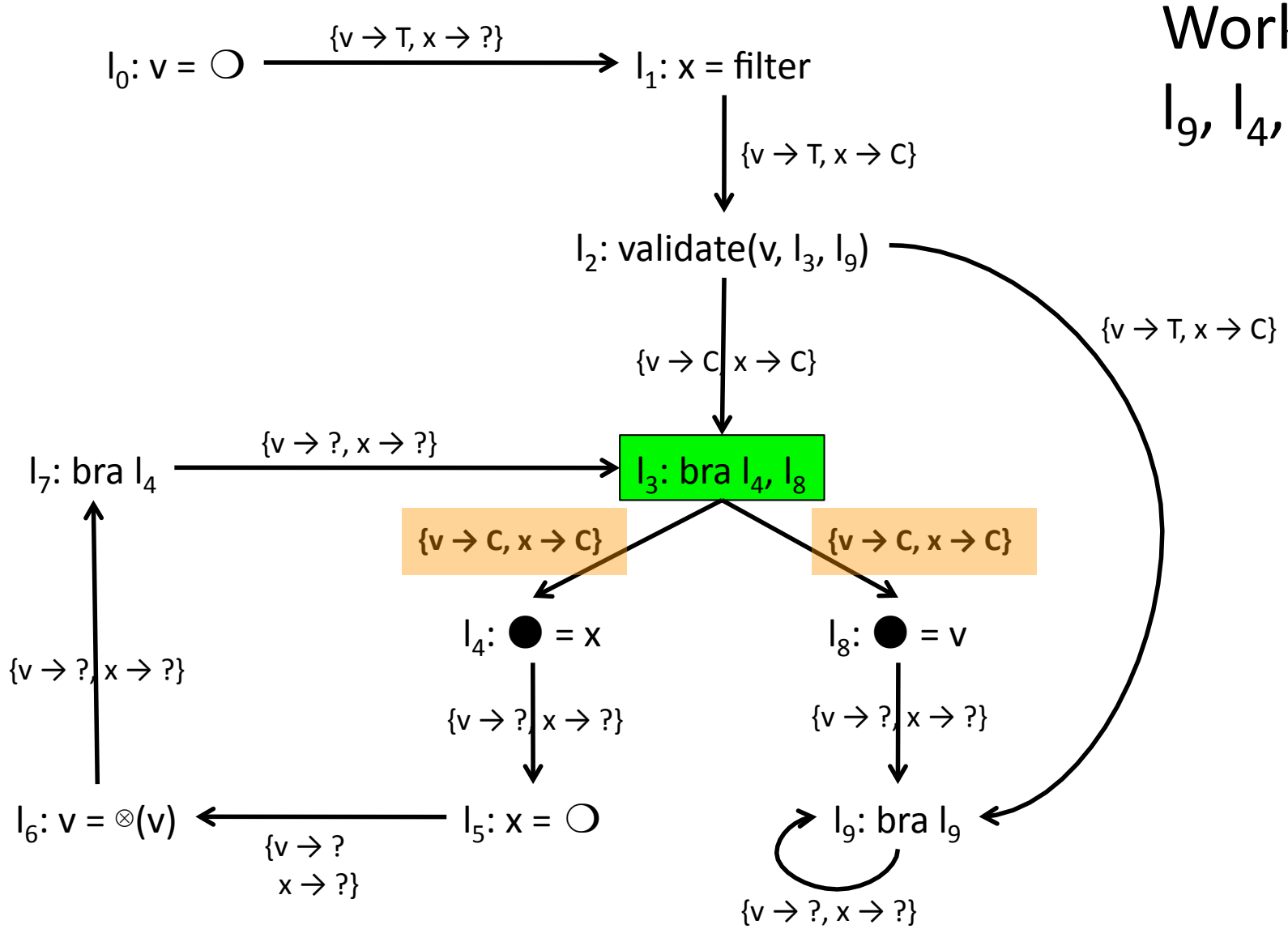

Worklist:

$l_2$

# Example of dense approach

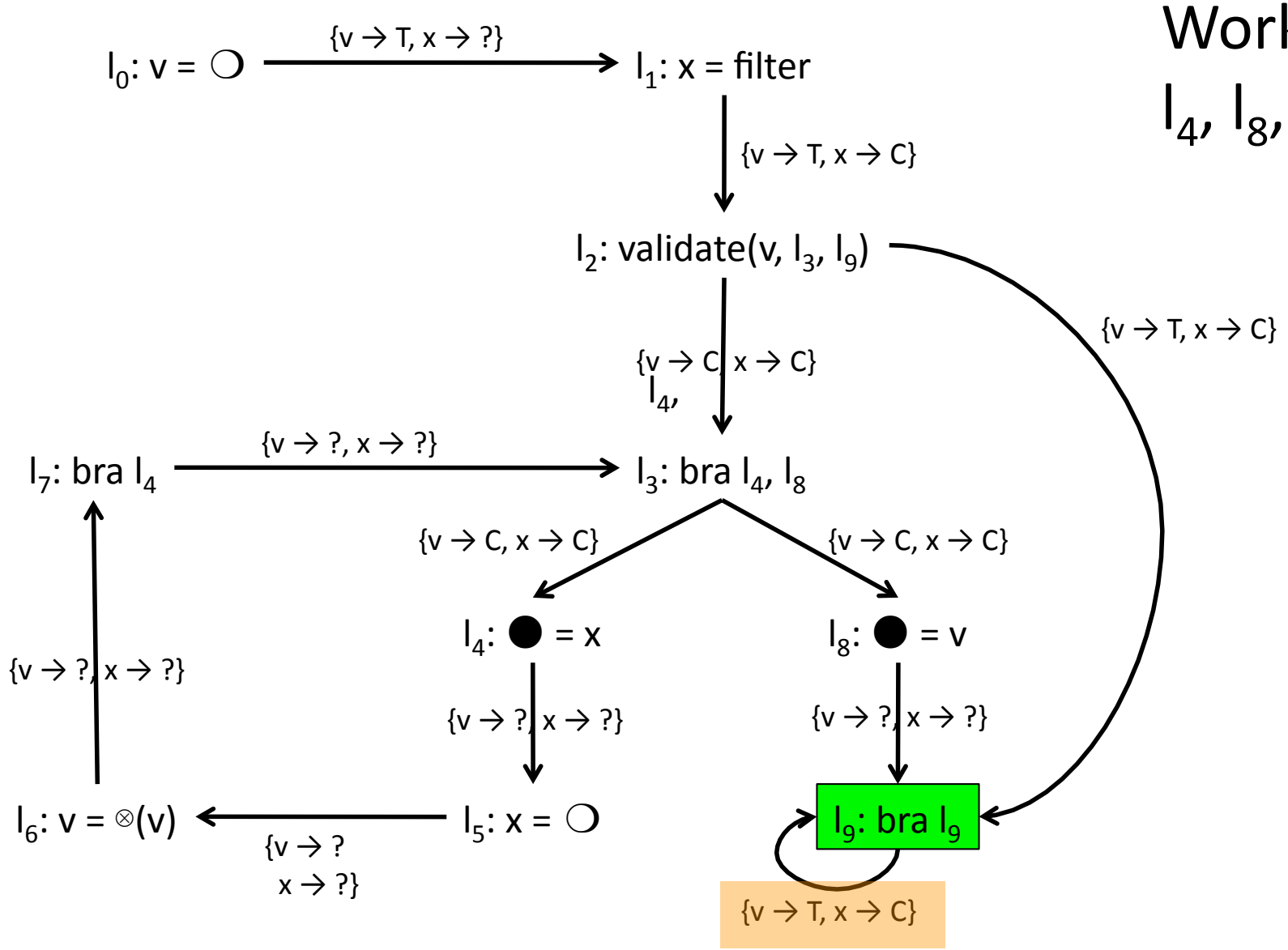


# Example of dense approach



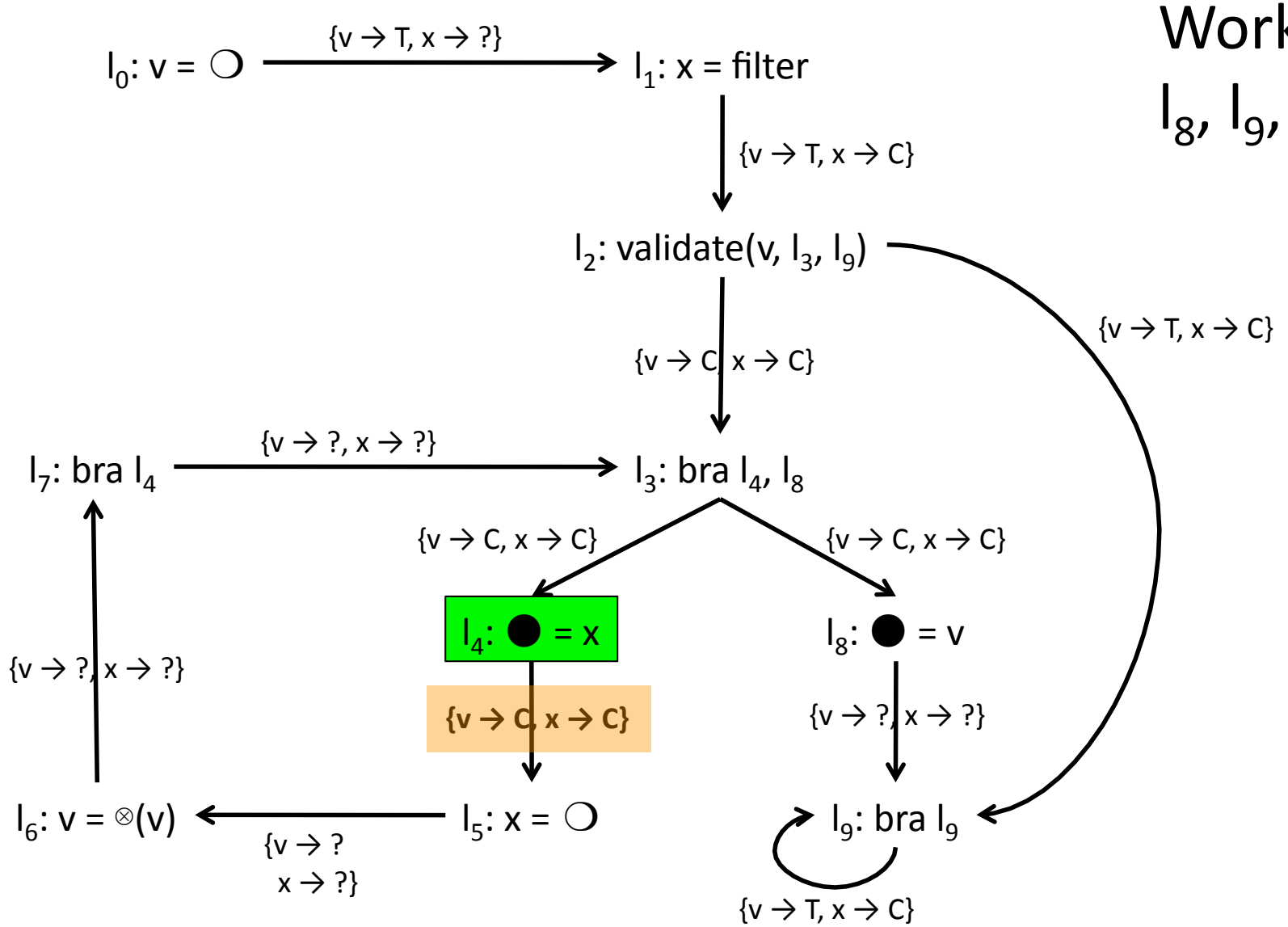

Worklist:
$l_9$, $l_4$, $l_8$

# Example of dense approach



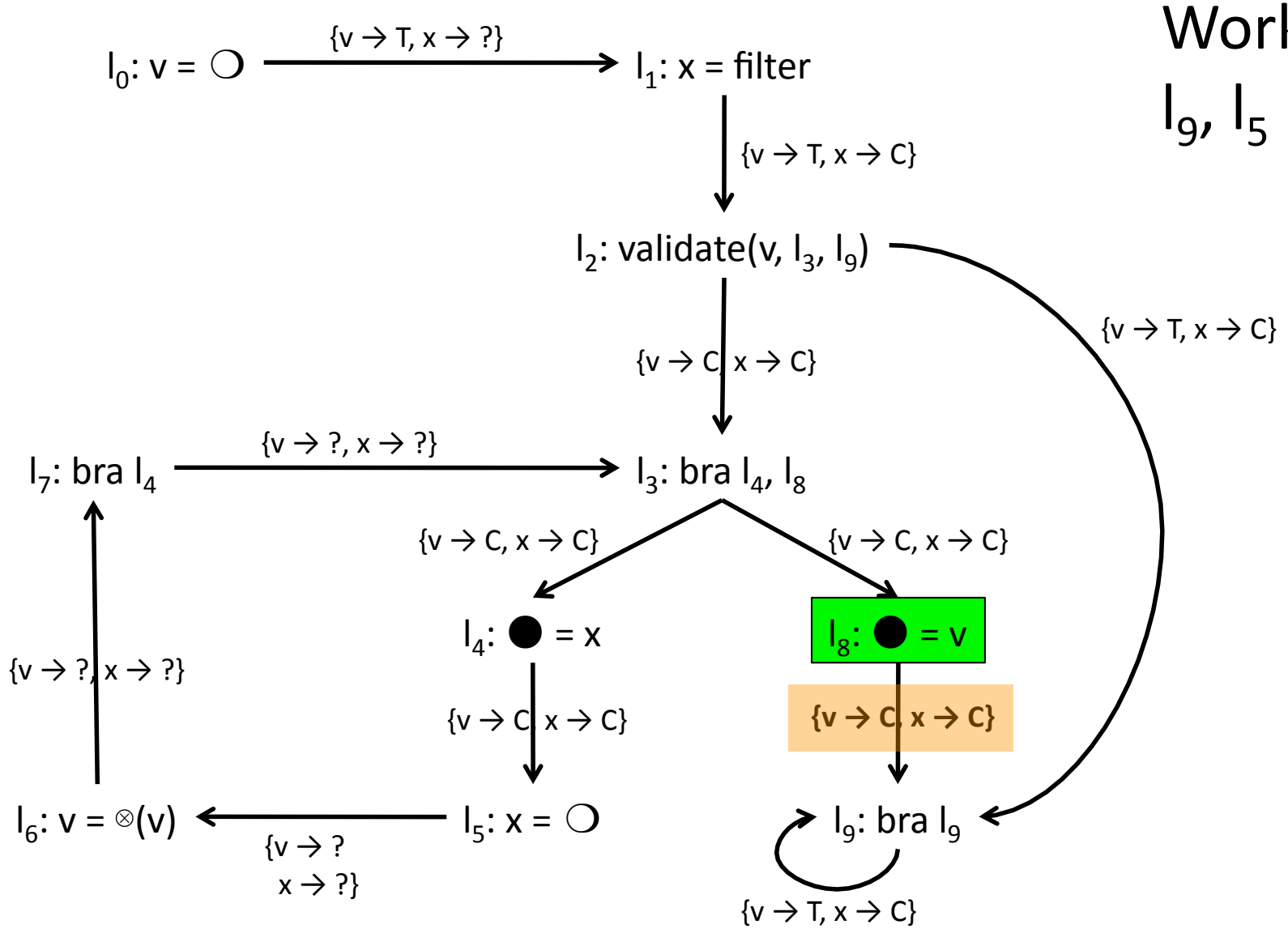

Worklist:
$l_4$, $l_8$, $l_9$

# Example of dense approach




Worklist:
$l_8$, $l_9$, $l_5$

# Example of dense approach




Worklist:
$l_9$, $l_5$

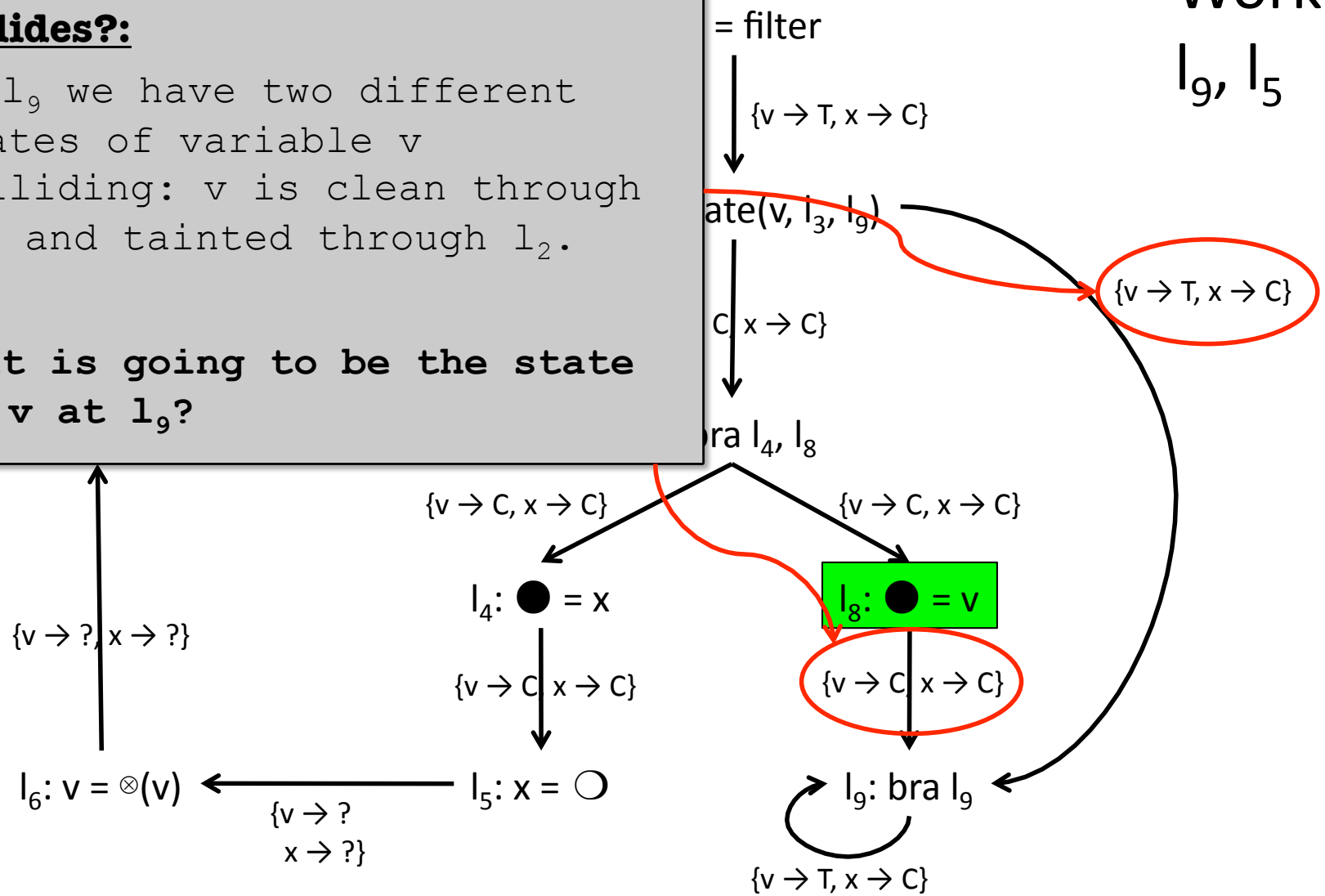
# Example of dense approach

**What happens when information collides?:**

At $l_9$ we have two different states of variable v colliding: v is clean through $l_8$, and tainted through $l_2$.

**What is going to be the state of v at $l_9$?**

Worklist:
$l_9$, $l_5$



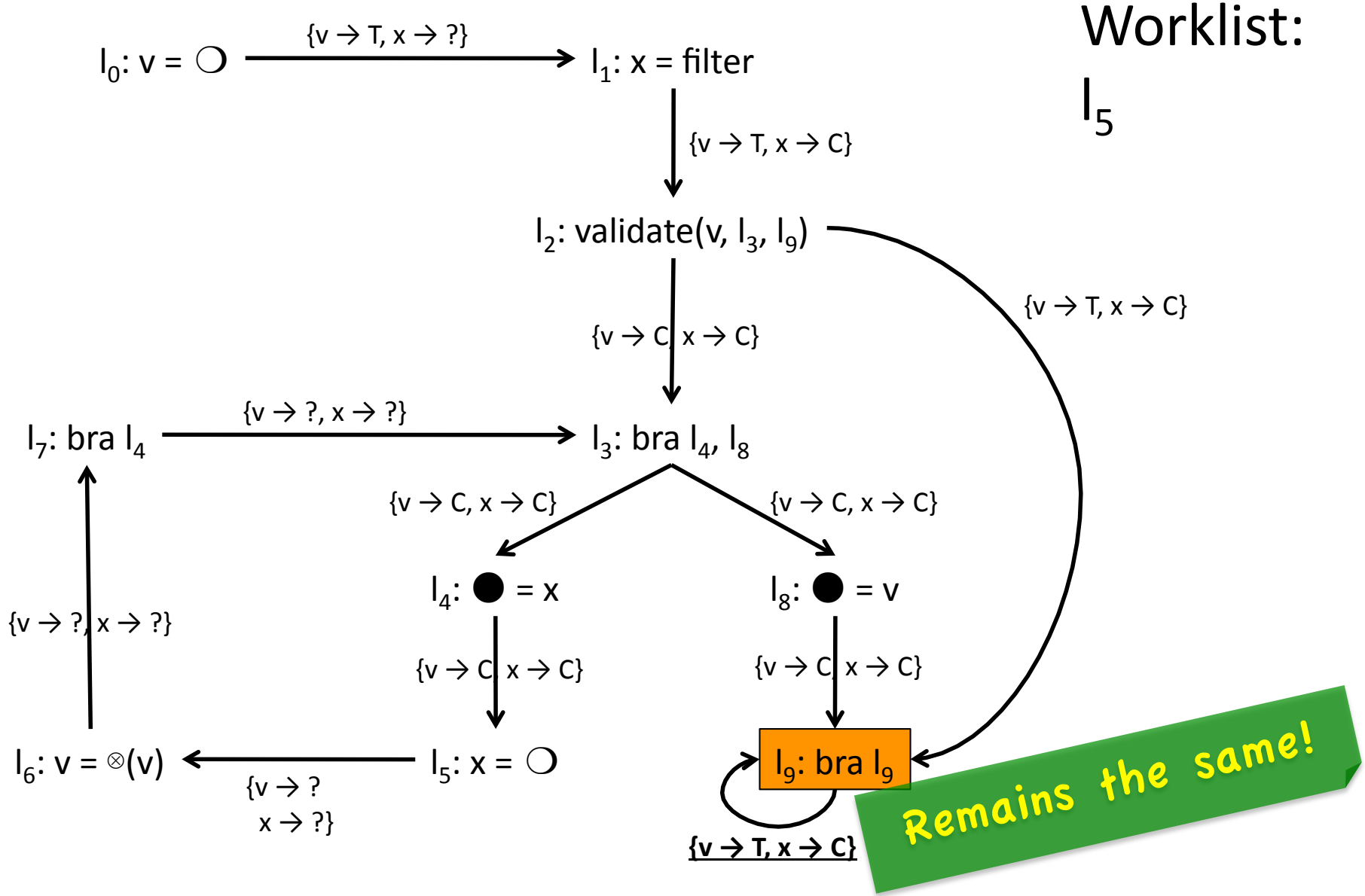
# The Meet Operator

| $\wedge$ | Undefined | Clean | Tainted |
|---|---|---|---|
| Undefined | Undefined | Clean | Tainted |
| Clean | Clean | Clean | Tainted |
| Tainted | Tainted | Tainted | Tainted |

- The meet operator defines what happens at the joining points in the program.
- We can easily extends its definition to our product lattice, e.g., {(a, tainted), (b, clean)} $\wedge$ {(a, clean), (b, undefined)} = {(a, tainted), (b, clean)}

Is this analysis may or must?

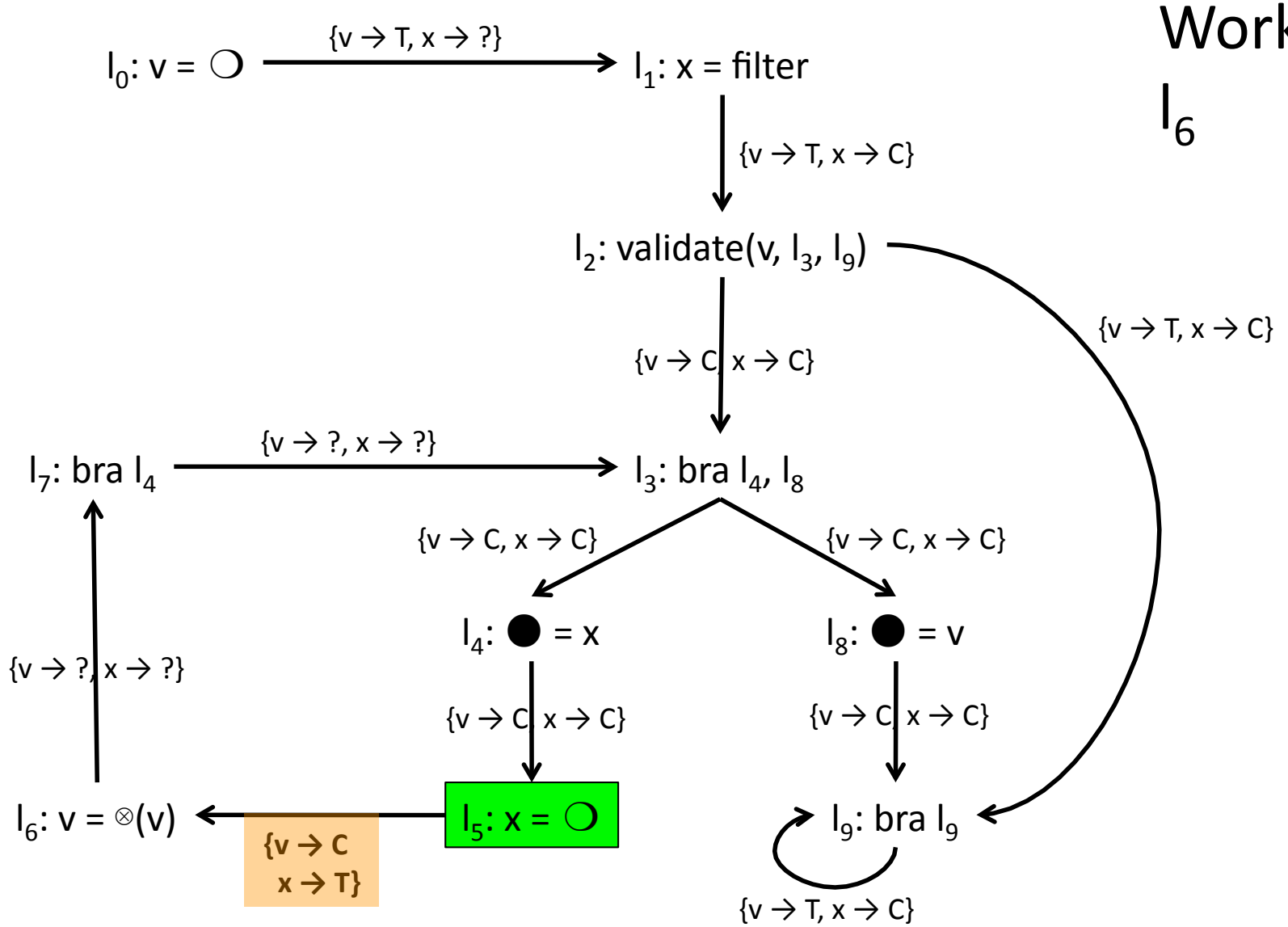
# Example of dense approach



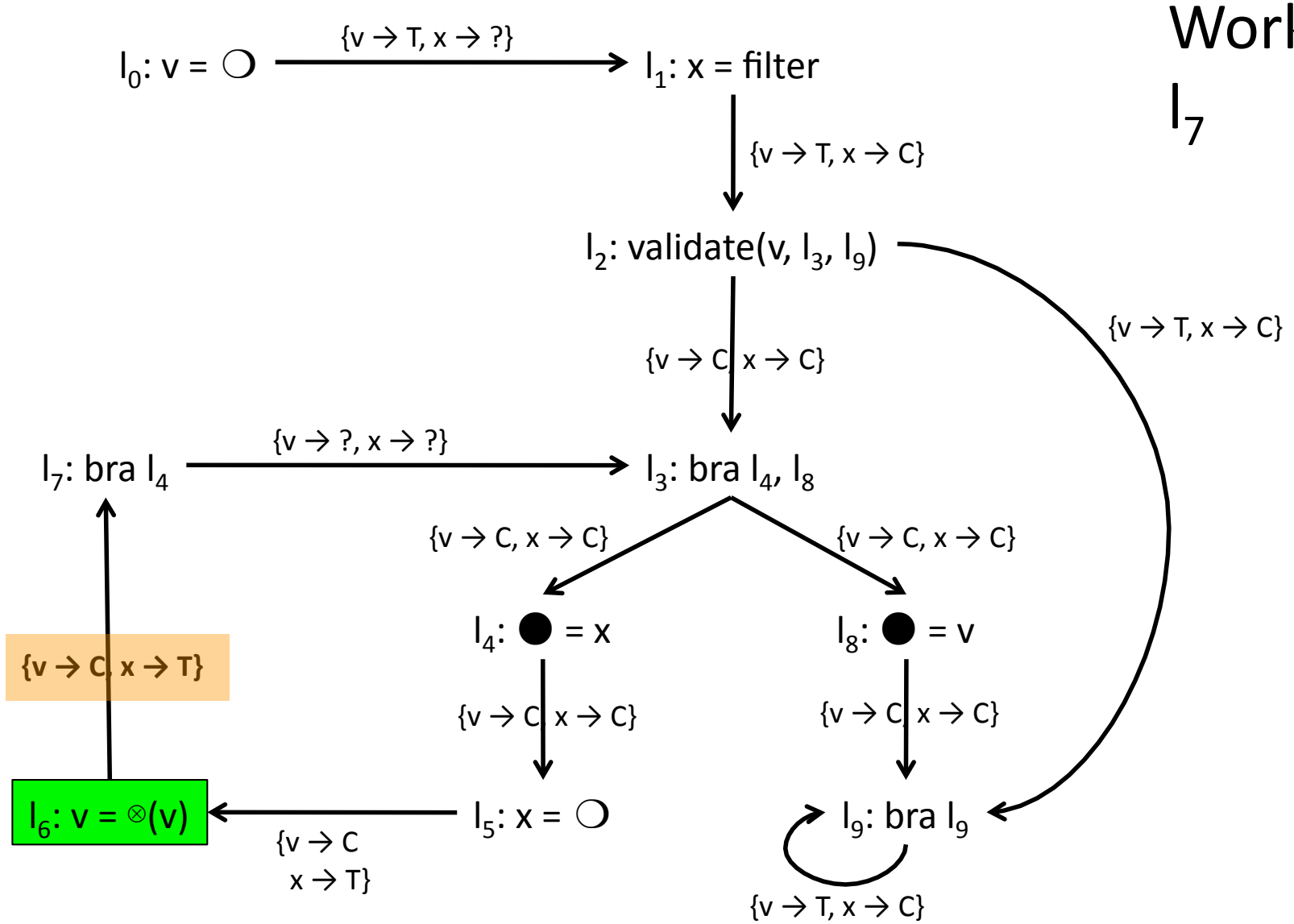

Worklist:

$l_5$

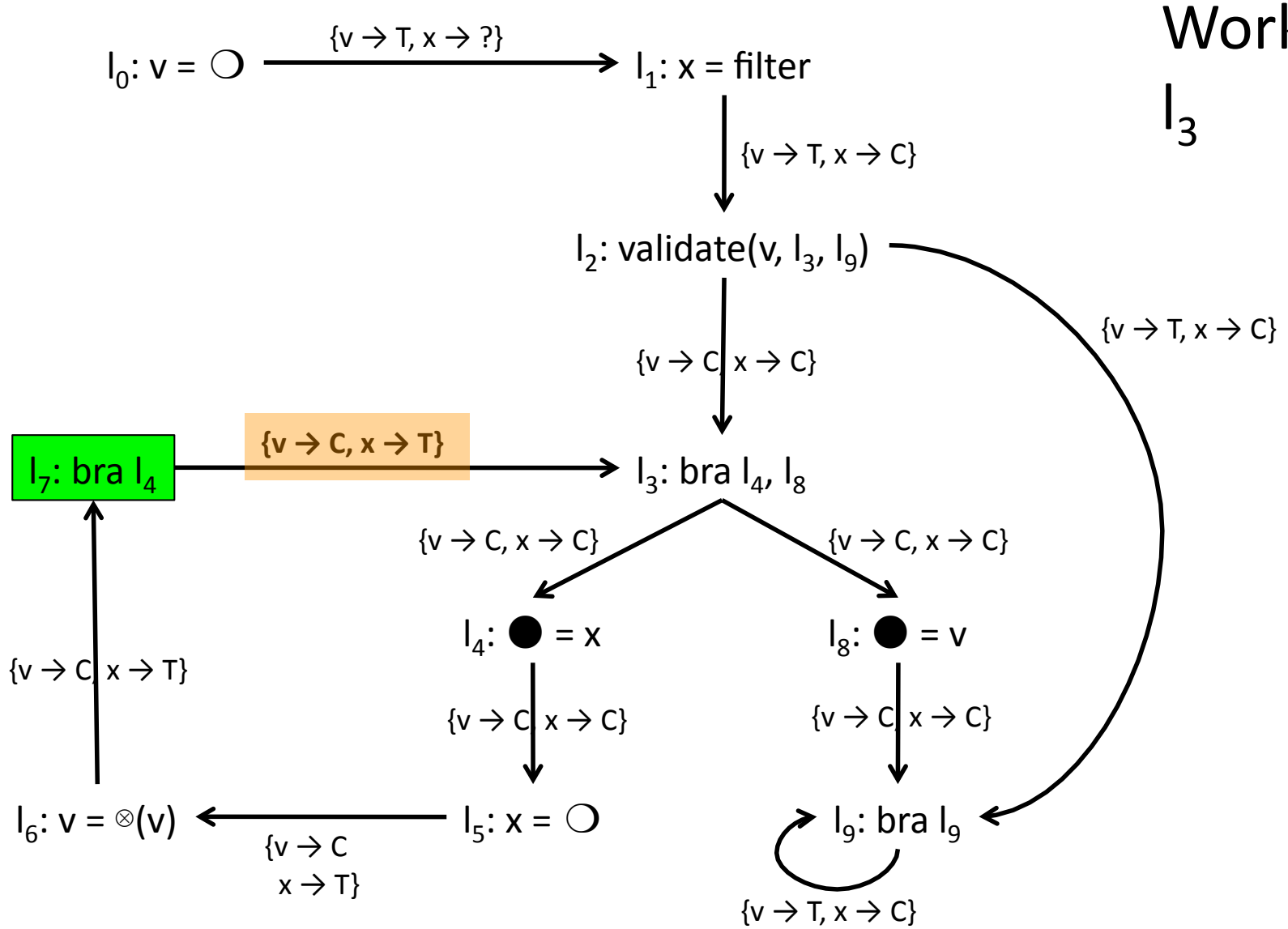
# Example of dense approach



# Example of dense approach



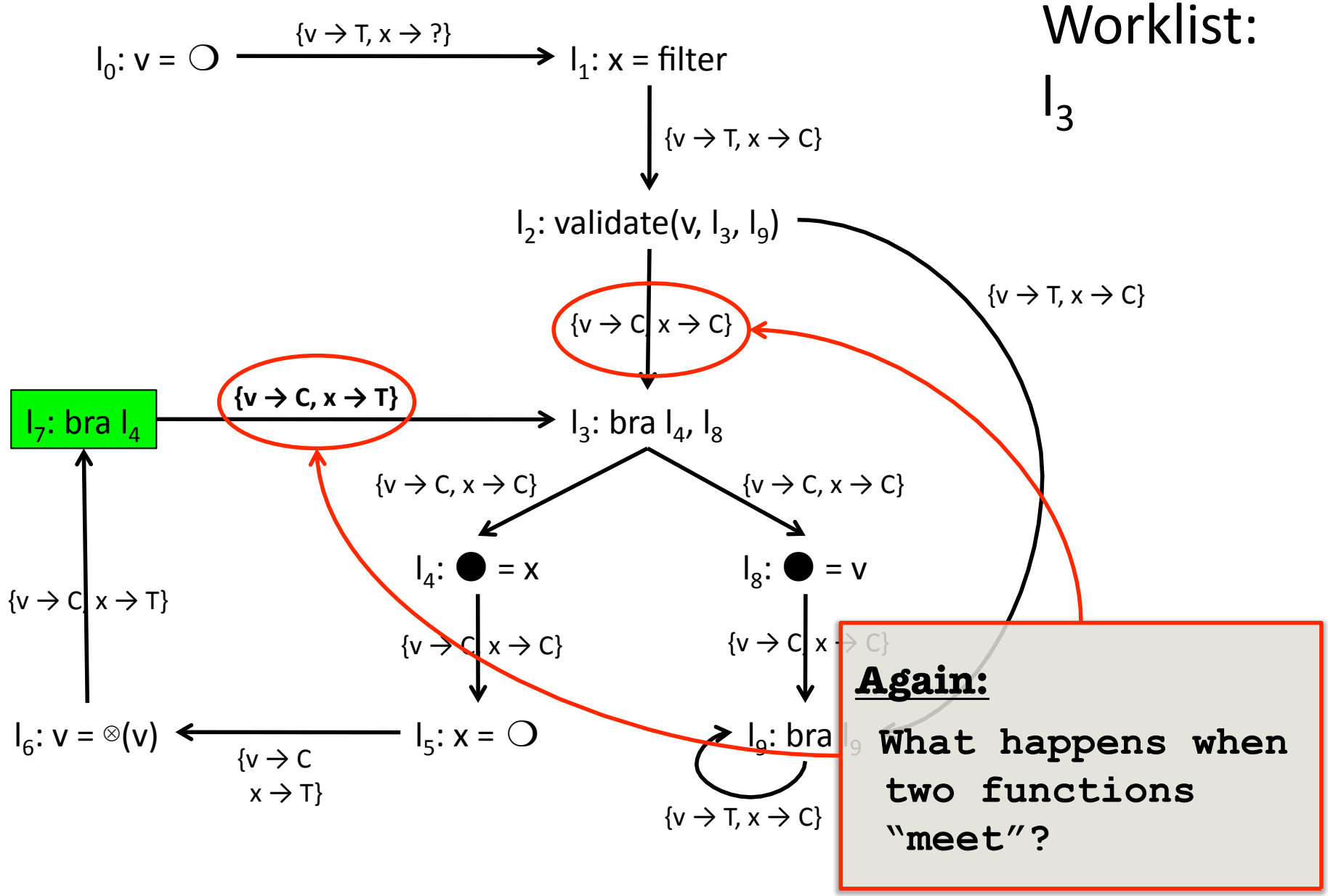
# Example of dense approach



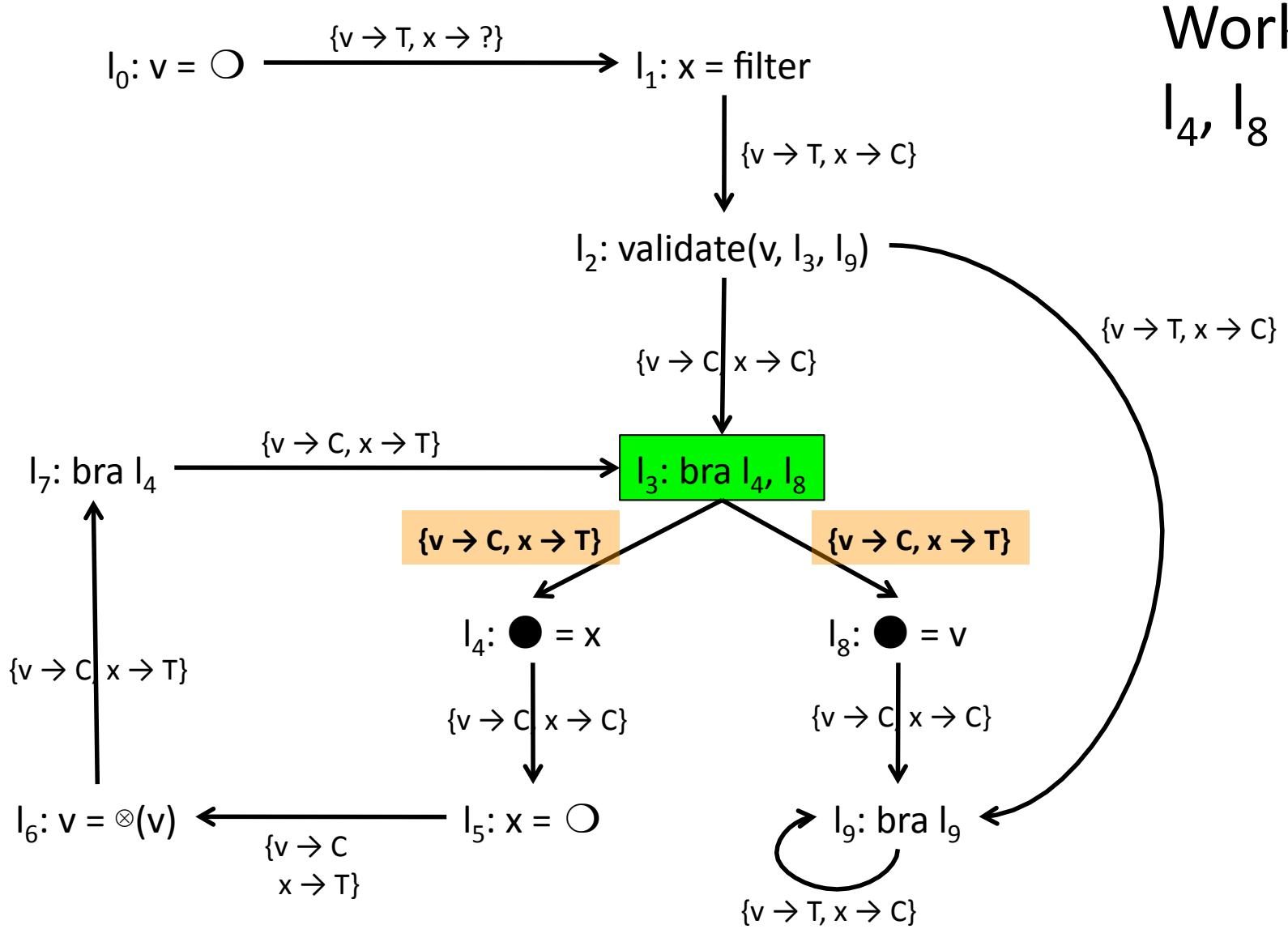

Worklist:

$l_3$

# Example of dense approach

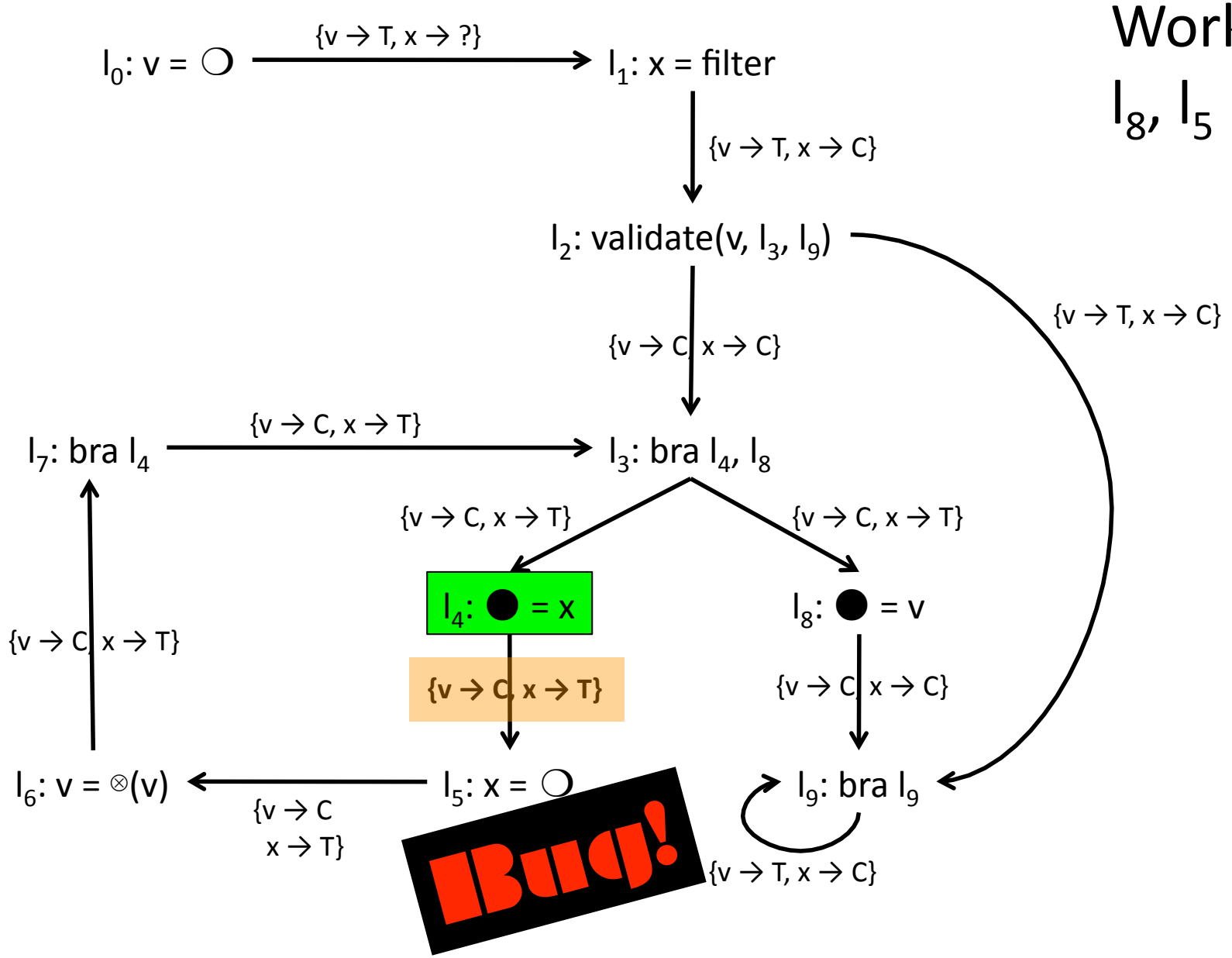


# Example of dense approach

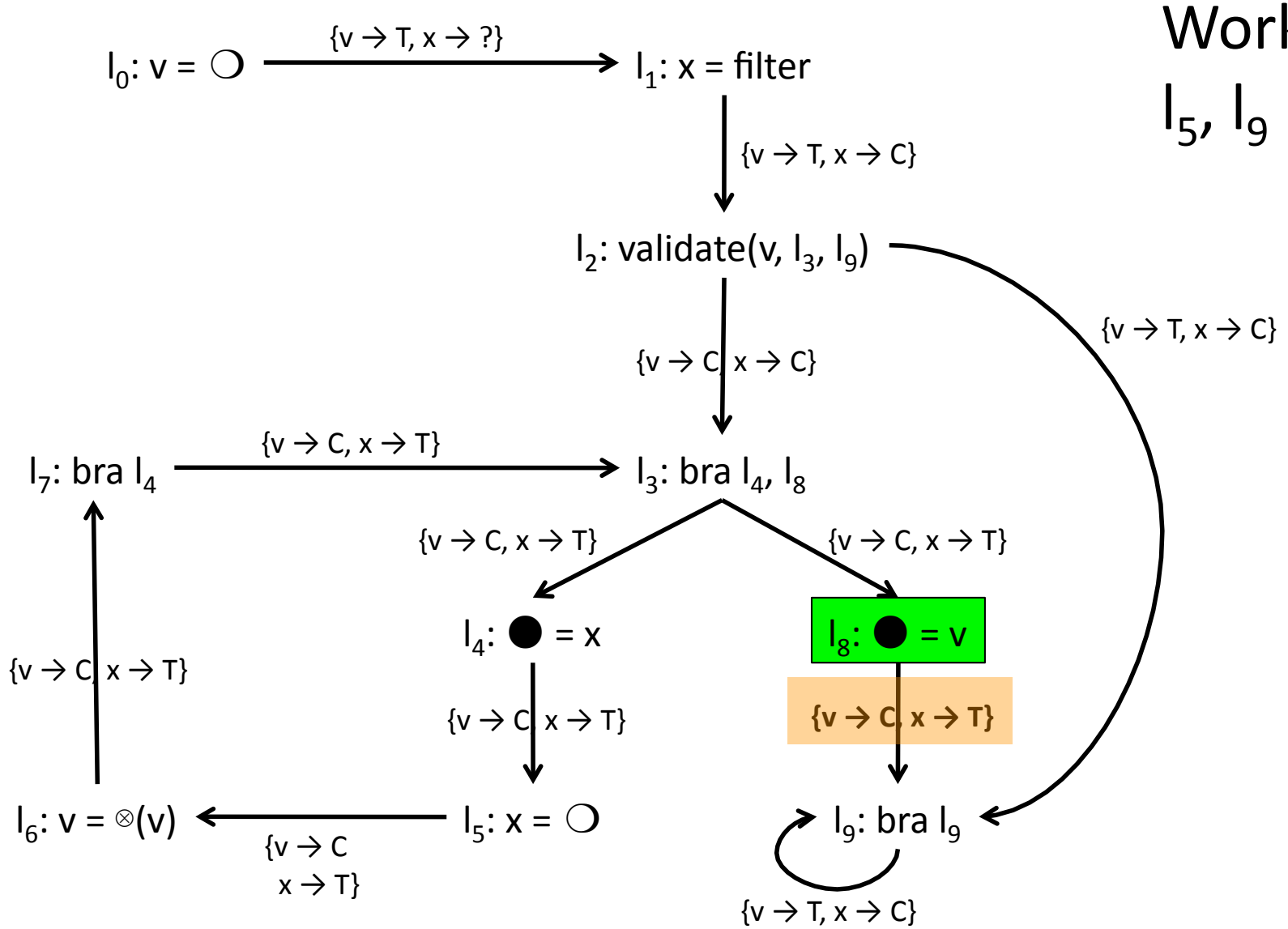



Worklist:
$l_4$, $l_8$

# Example of dense approach

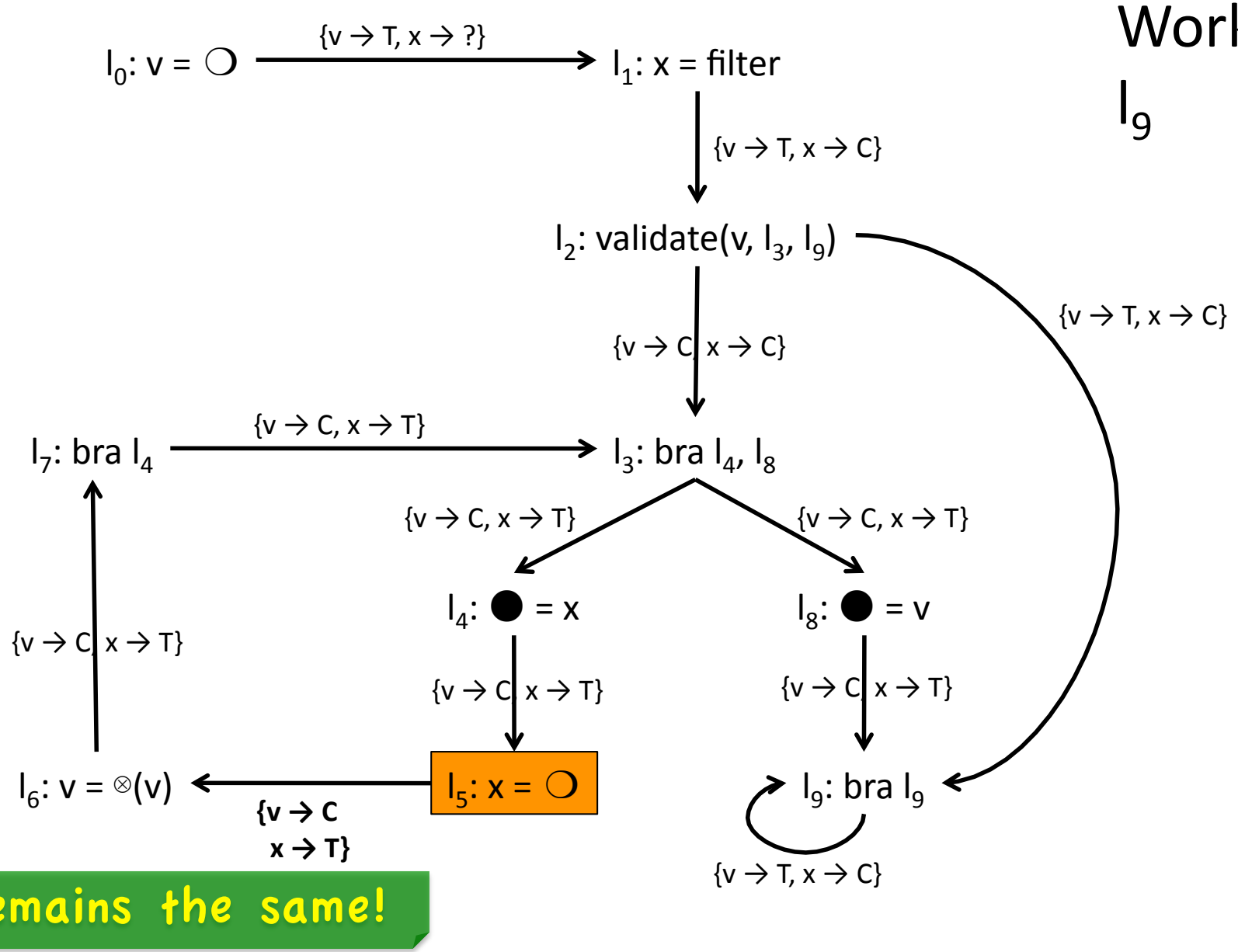


# Example of dense approach

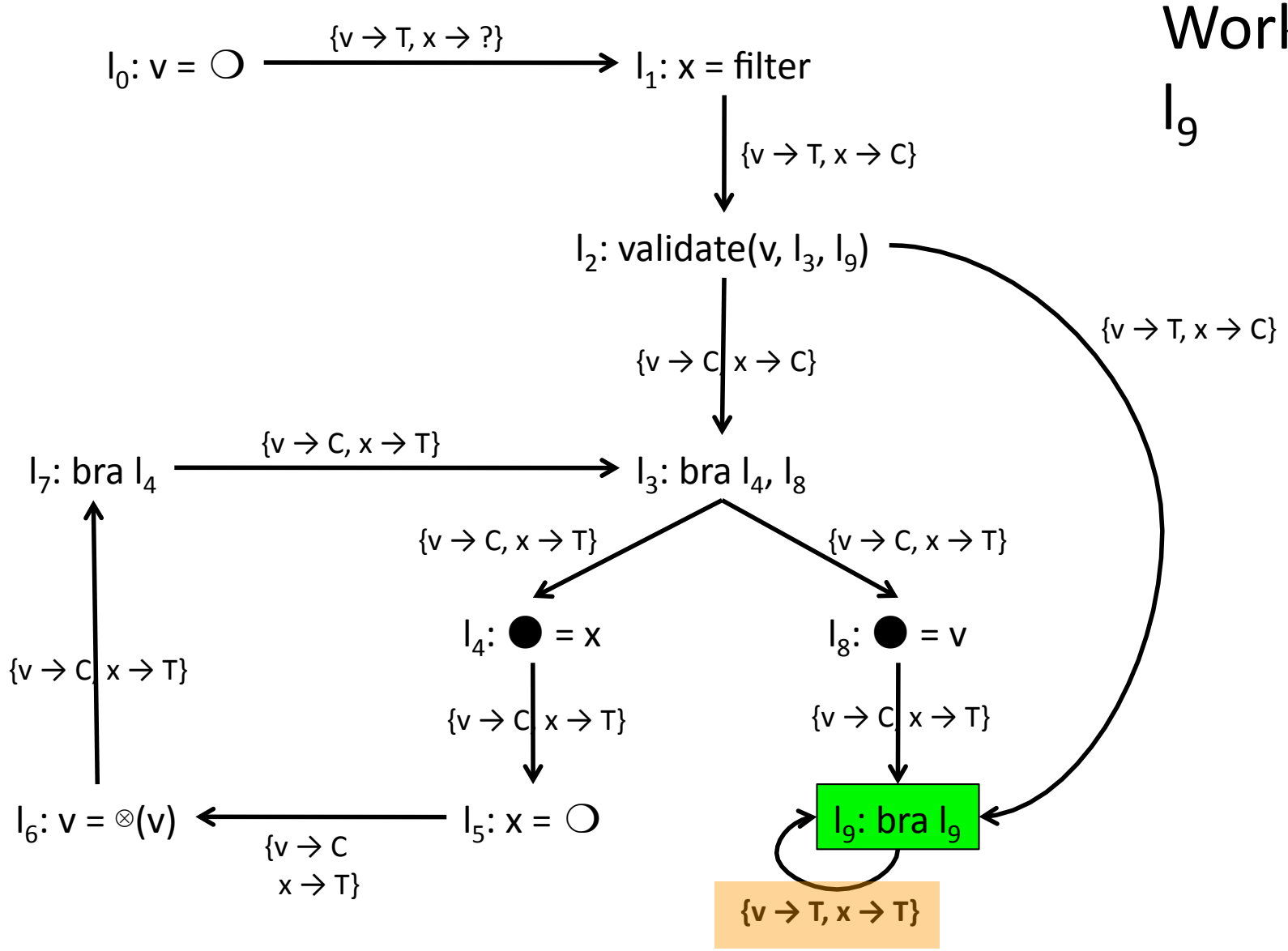



Worklist:
$l_5$, $l_9$

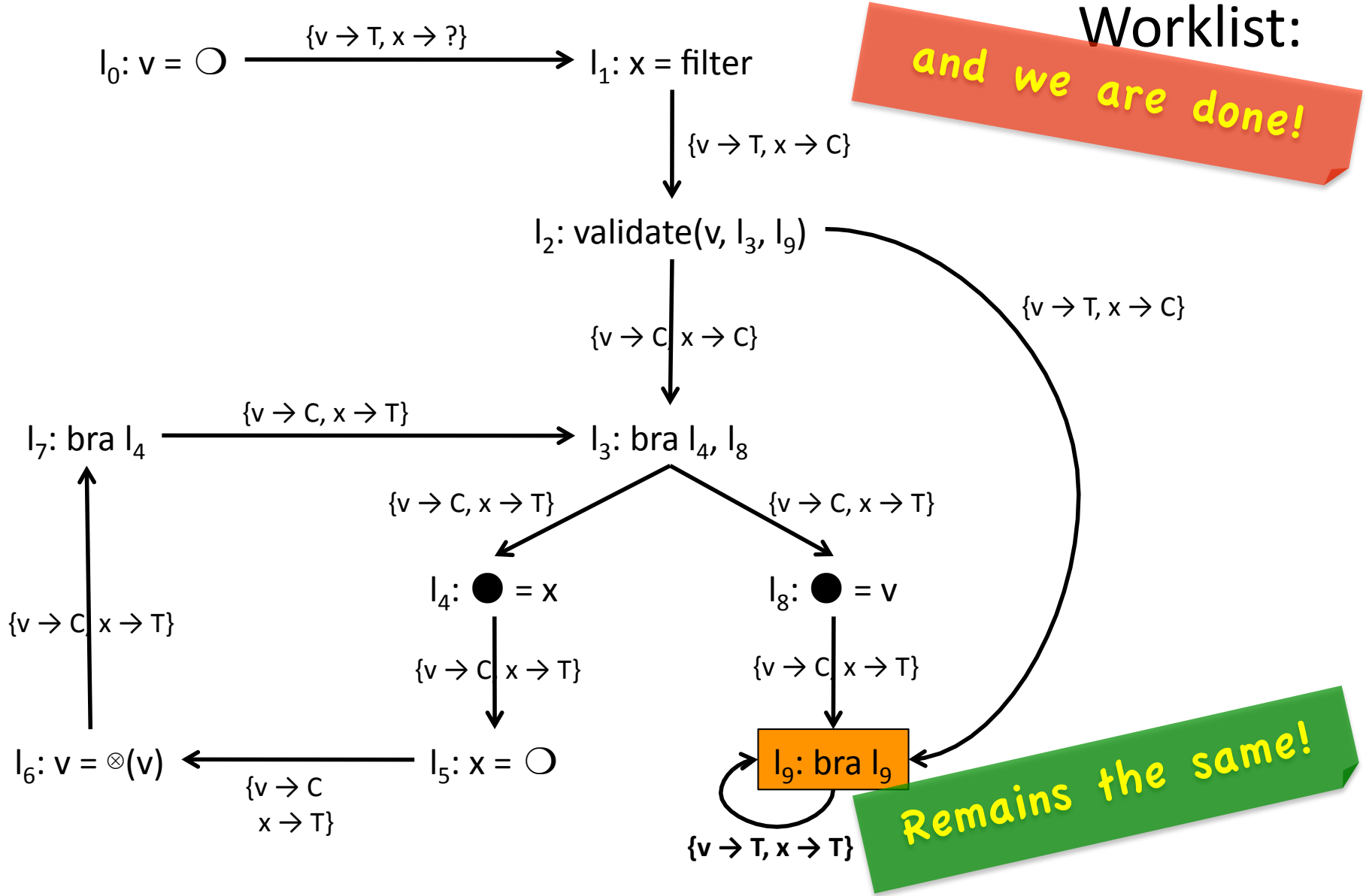
# Example of dense approach



# Example of dense approach



# Example of dense approach



PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Ensuring Termination

- Does this algorithm always terminates?

- So, what is the complexity of this algorithm?

PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Ensuring Termination

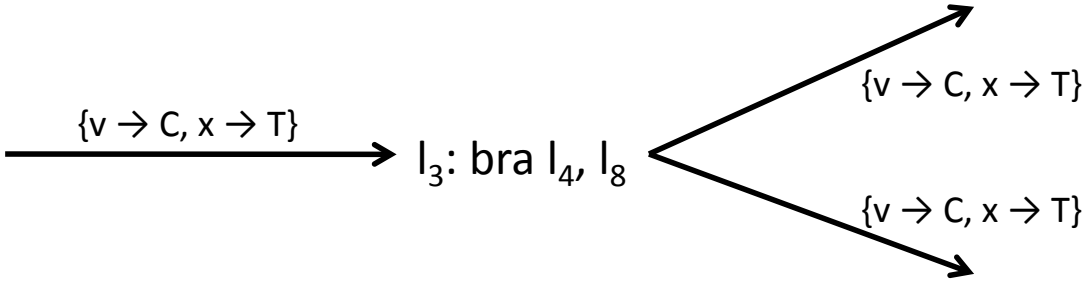
- Does this algorithm always terminates?
  - It does, because each variable can be mapped to either ?, clean or tainted. Once it reaches tainted, it does not change anymore. If every variable in a program point becomes tainted, that program point will not be added to the work list again.
- So, what is the complexity of this algorithm?
  - It is $O(P \times V \times M)$, where P is the number of program points, V is the number of variables, and M is the number of predecessors of a program point. Usually, $O(P) = O(V)$; and $O(M) = O(1)$. Thus, we have $O(V^2)$.

# SPARSE TAINTED FLOW ANALYSIS

DCC 888

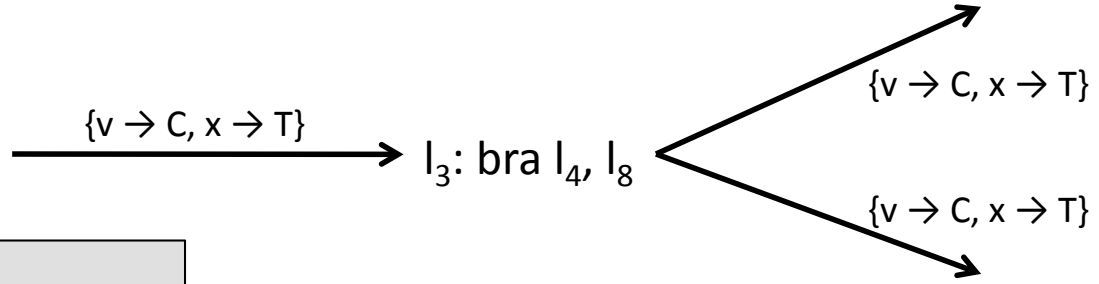
# Problems with dense analyses

- Lots of redundant information
  - Some nodes just pass forward the information that they receive.
  - These nodes are bound to identity transfer functions:



# Problems with dense analyses

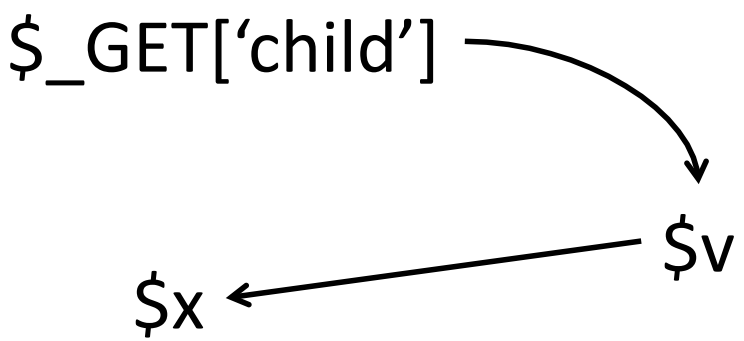
- Lots of redundant information
  - Some nodes just pass forward the information that they receive.
  - These nodes are bound to identity transfer functions:




We had two notions of "path". Do you remember the second?

# Another notion of path

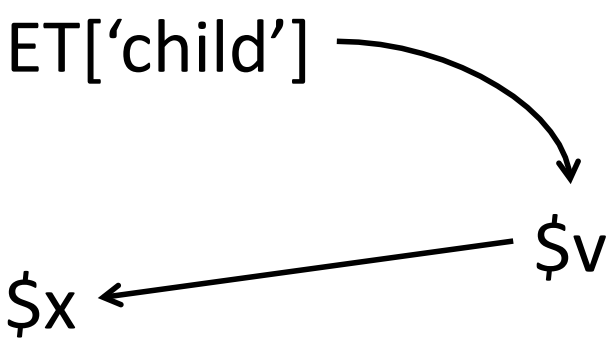
```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```




**A path is a chain of data dependences in a program**

# Sparse Analysis

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

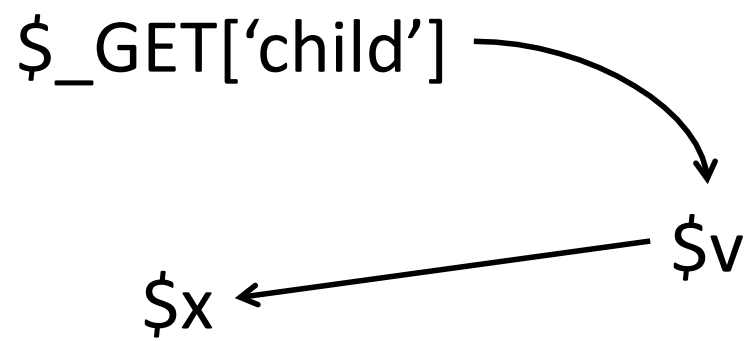



- If the "state" of a variable is always the same, we can bind this state, e.g., clean or tainted, to the variable itself.

Is the state of $x always the same in the program above?

# Sparse Analysis

```
$v = DB.get($_GET['child']);
$x = "";
if (DB.isMember($v)) {
  while (DB.hasParent($v)) {
    echo($x);
    $x = $_POST['$v'];
    $v = DB.getParent($v);
  }
  echo($v);
}
```

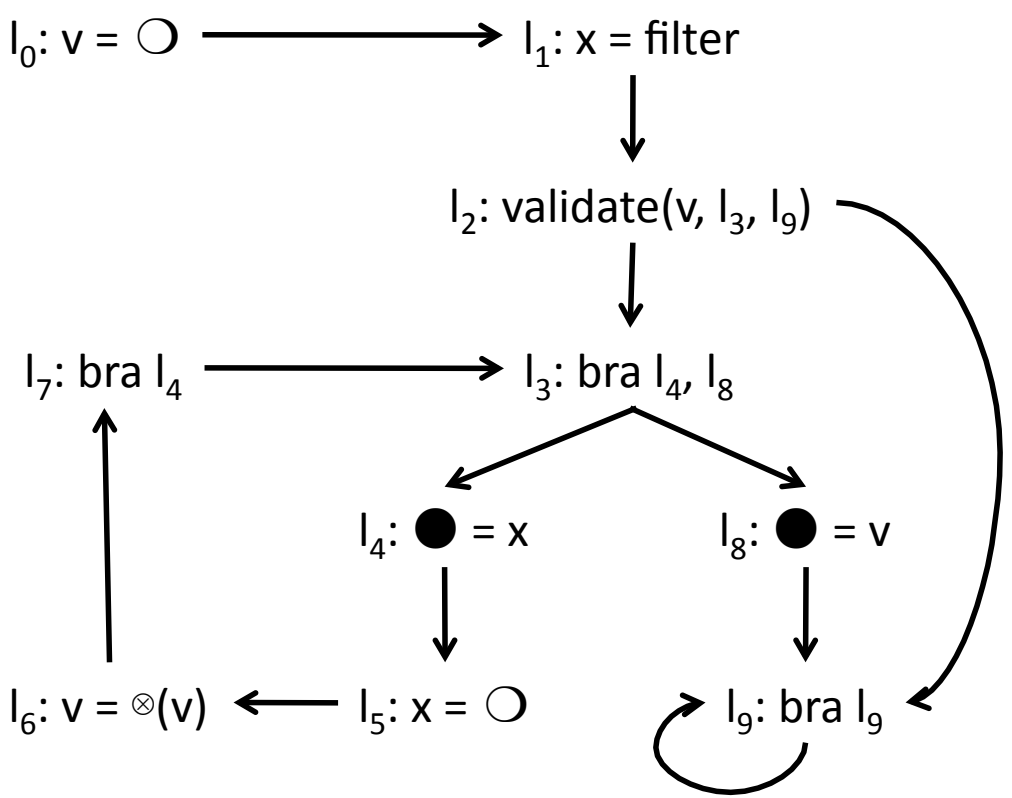



1) How can we ensure that the abstract state of a variable is always the same?

2) This property will give us a sparse analysis. Do you remember what is a sparse analysis?

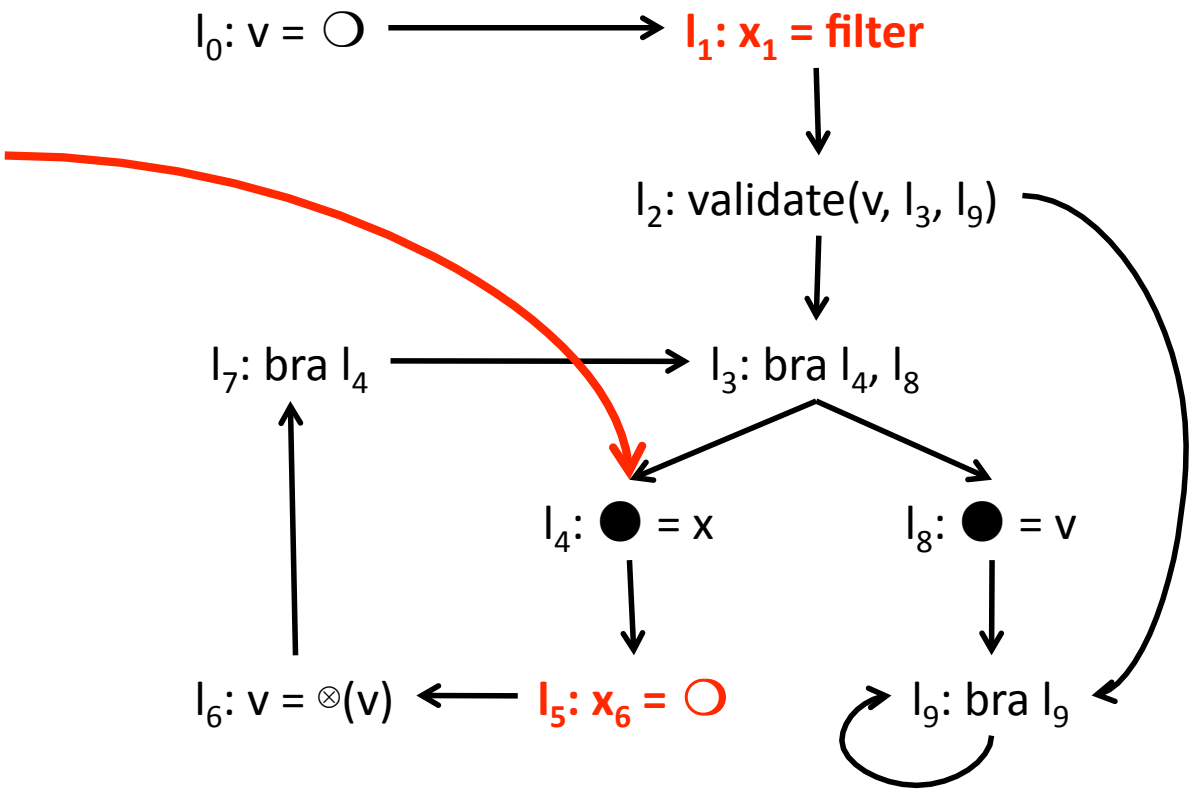
# Static Single Assignment

- The key is to ensure that each variable is defined in at most one site inside the program text.
- The name x is defined twice. We need to rename it!



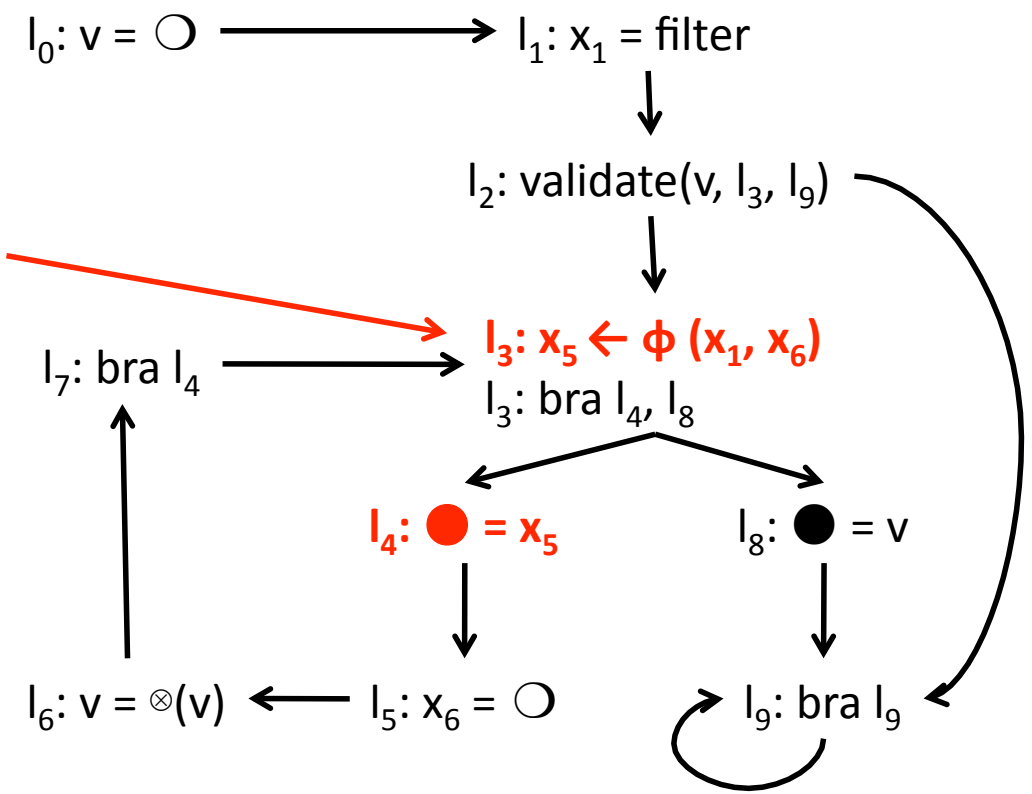
# Static Single Assignment

- The key is to ensure that each variable is defined in at most one site inside the program text.
- The name x is defined twice. We need to rename it!
- But what is x at $l_4$?



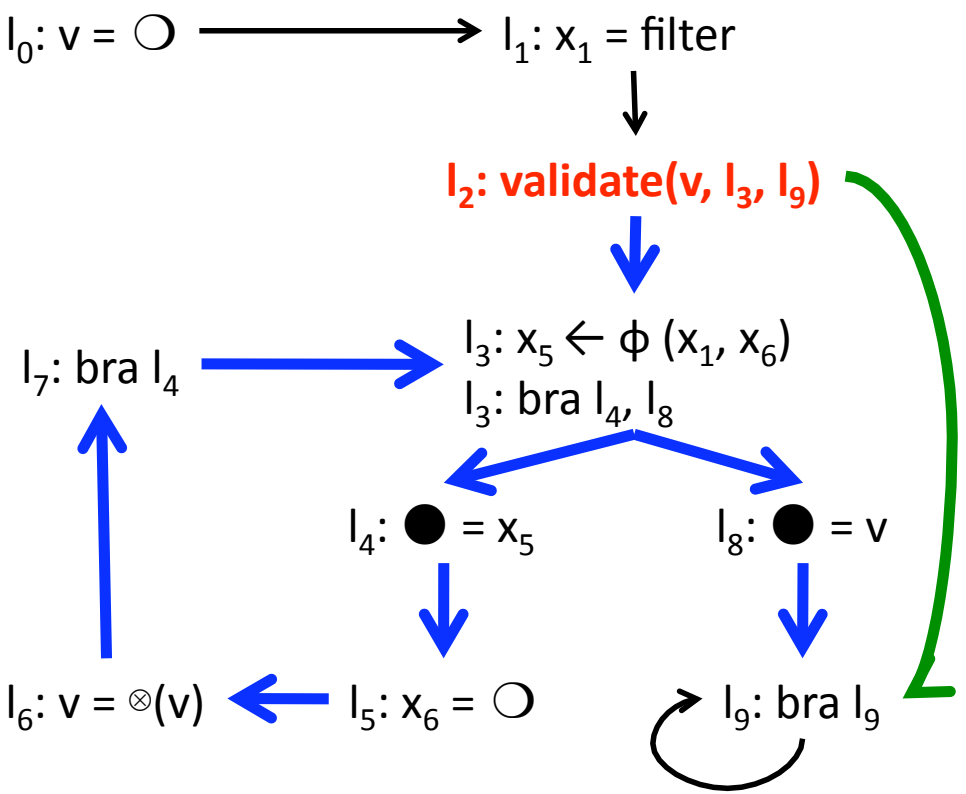
# Static Single Assignment

- The key is to ensure that each variable is defined in at most one site inside the program text.
- The name x is defined twice. We need to rename it!
- But what is x at $l_4$?
- We use **phi-functions** to merge different variables into a single name.



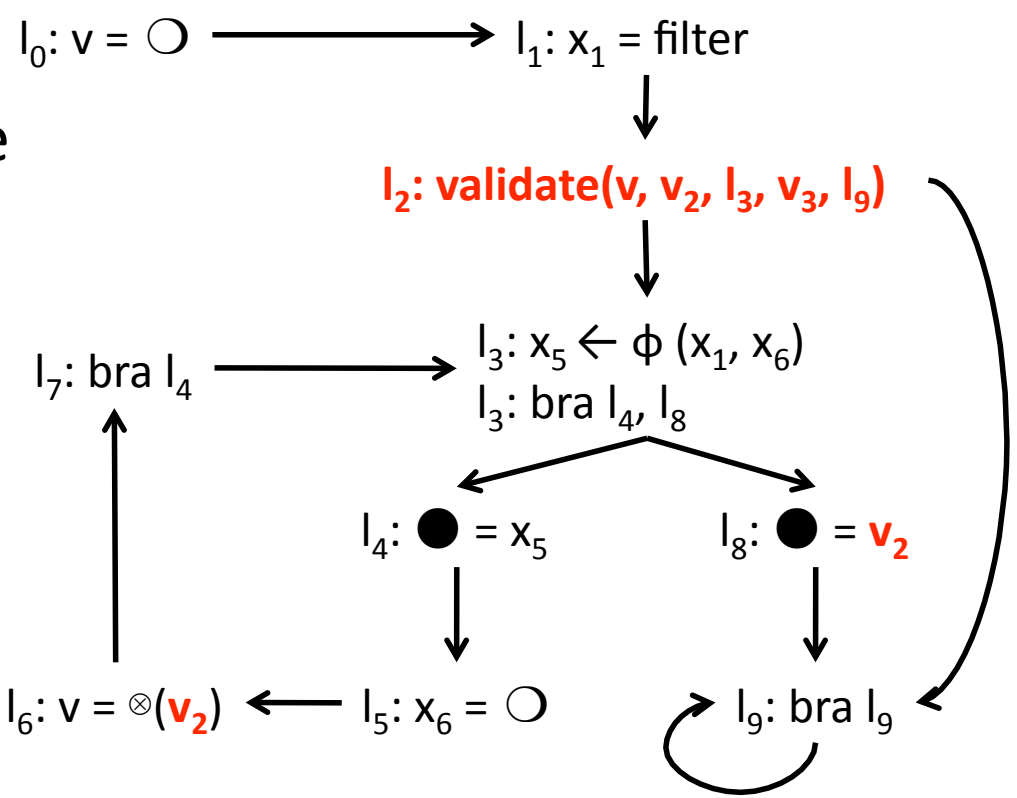
# Static Single Assignment

- The variable v defined at $l_0$ is clean at some parts of the program, and tainted at others. Can you identify them?
- We can "learn" information about v from the *validator*.
- But we still would like to associate v with a single abstract state, clean or tainted. **How**?



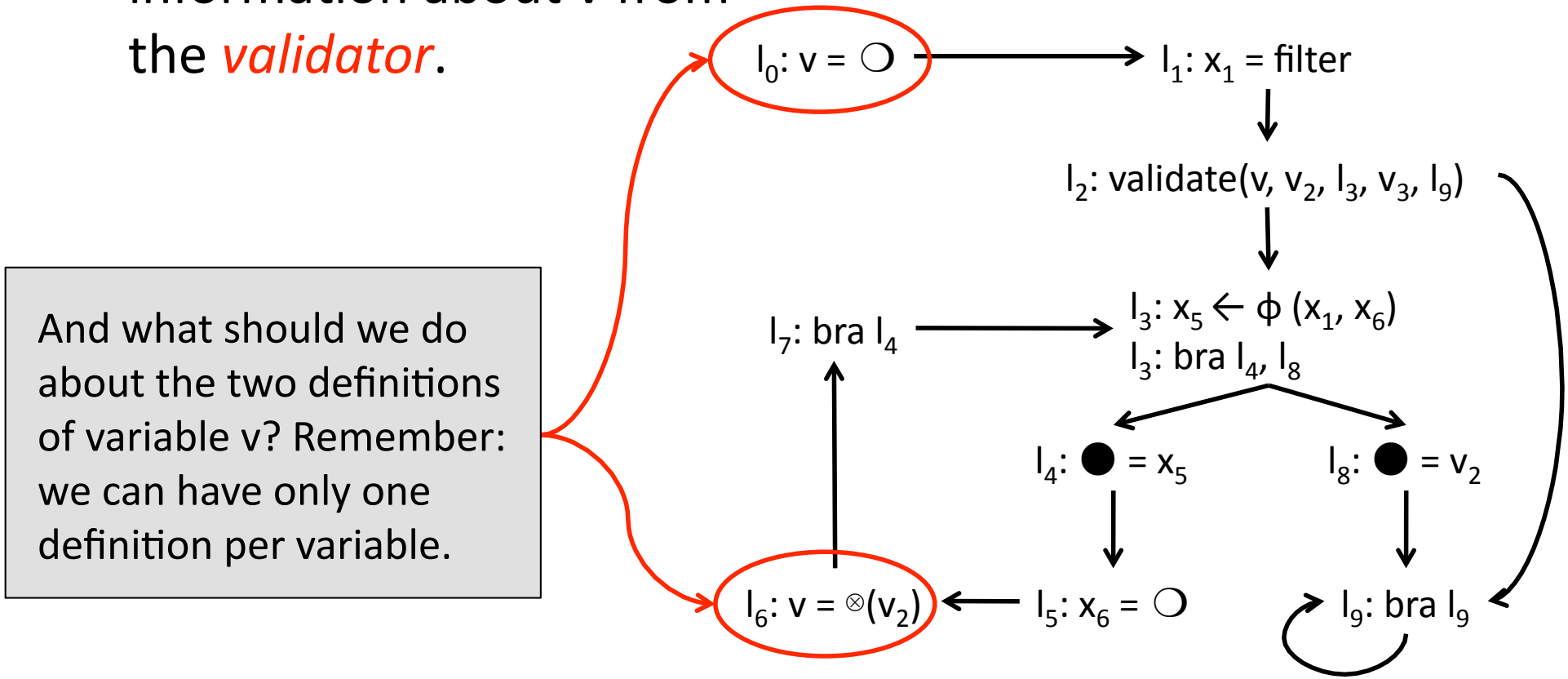
# Validators define new variable names

- The variable v defined at $l_0$ is clean in some parts of the program, and tainted at others. Can you identify them?
- We can "learn" information about v from the *validator*.
- Lets rename each variable that is validated. In this way, each validator defines two new names.



# Validators define new variable names

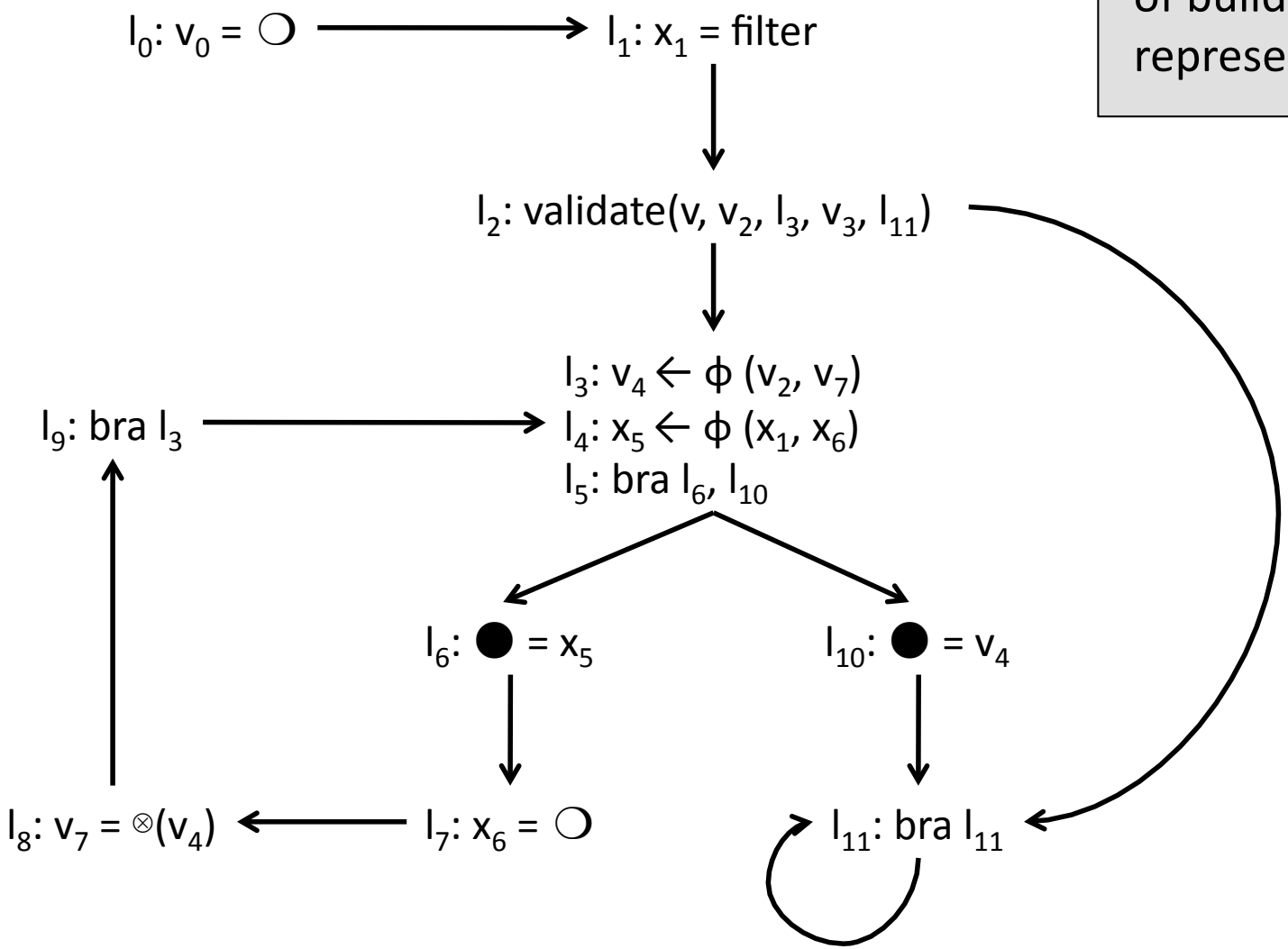
- The variable v defined at $l_0$ is clean in some parts of the program, and tainted at others. Can you identify them?
- We can "learn" information about v from the *validator*.




And what should we do about the two definitions of variable v? Remember: we can have only one definition per variable.

# Example of Extended-SSA form program

What is the complexity of building this program representation?



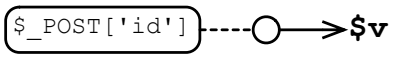
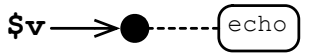
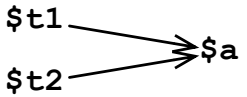
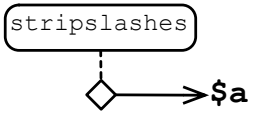
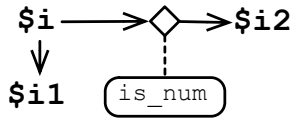
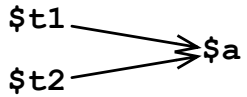
PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Sparse Analysis

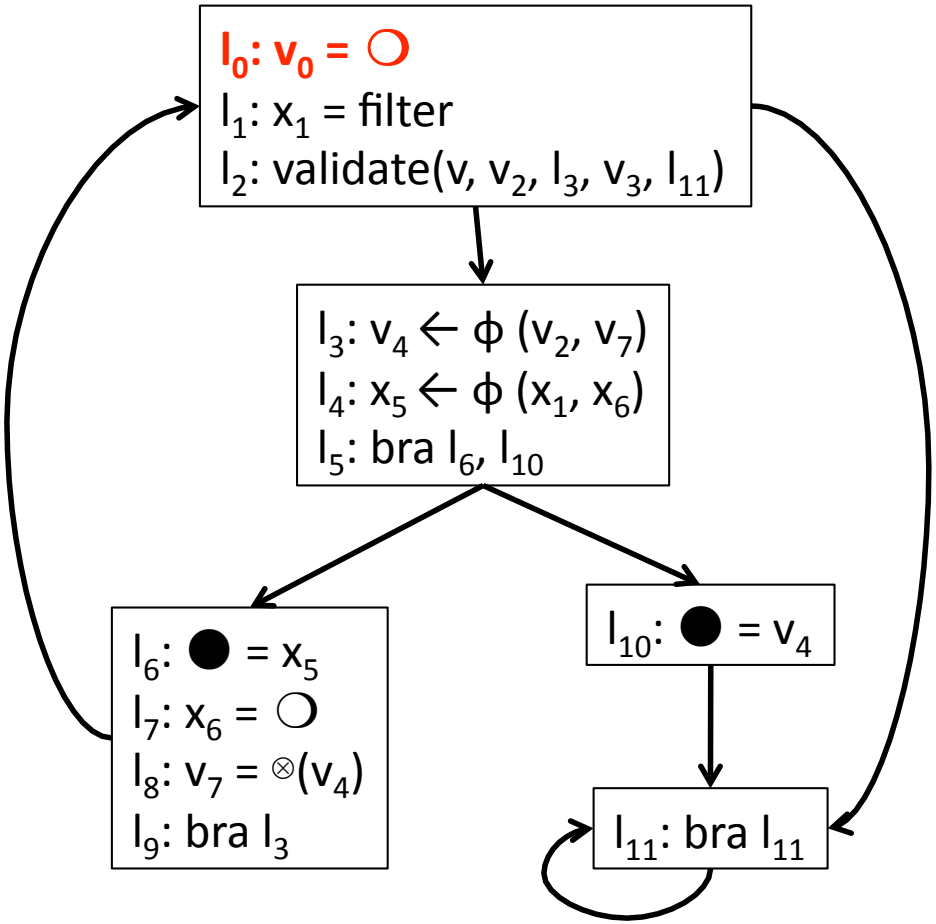
- Algorithm in three steps:
  - Convert the program to e-SSA form → $O(V^2)$
  - Build the constraint graph → $O(V^2)$
    - In practice, it is → $O(V)$
  - Traverse the constraint graph → $O(E)$ → $O(V^2)$

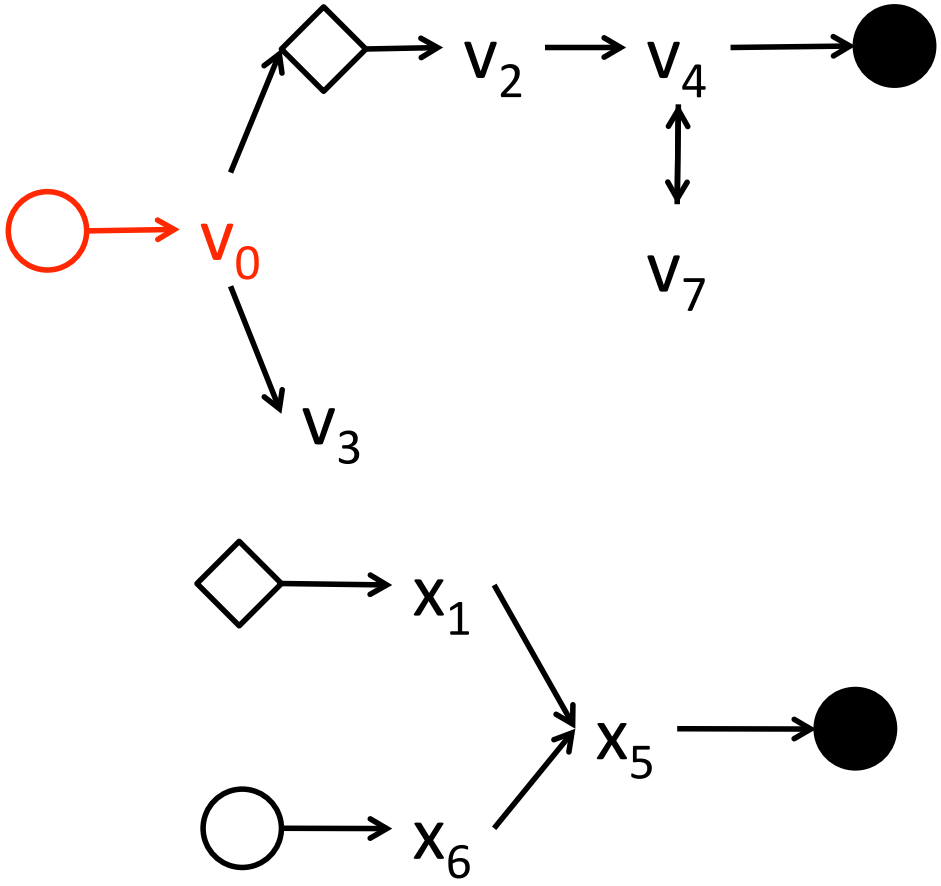
- We are assuming that V is the number of variables in the program.

# Building the Constraint Graph

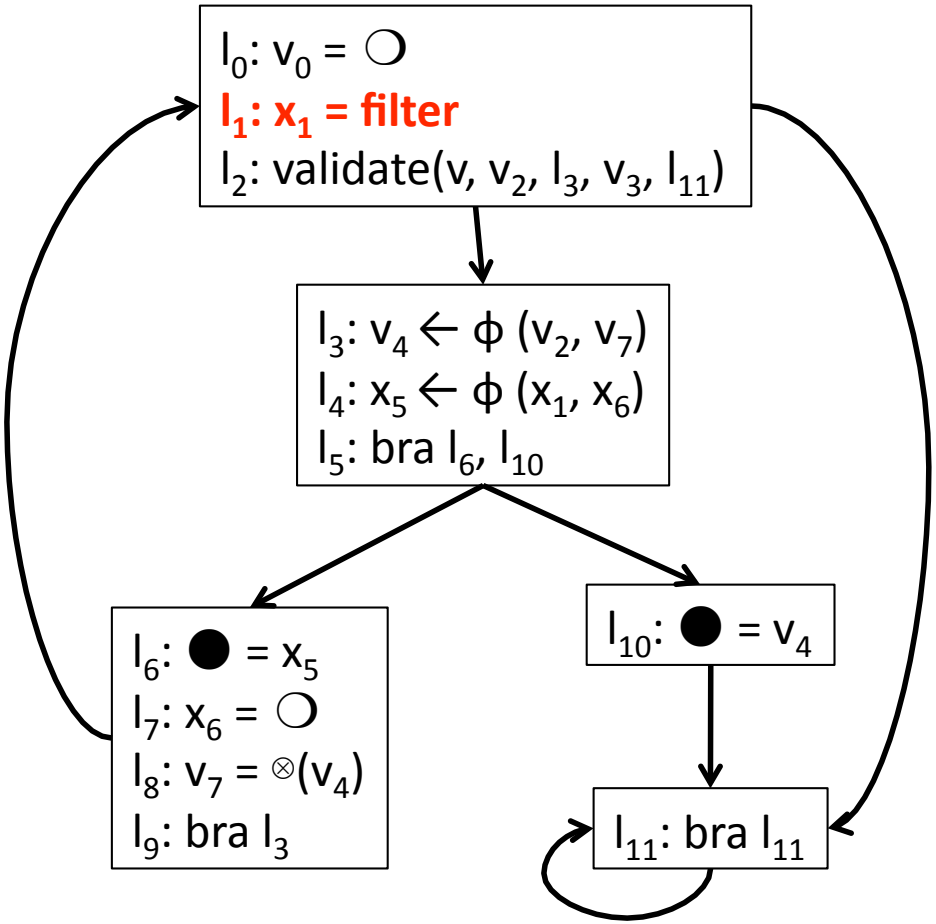
| Instruction | Example | Node |
|---|---|---|
| v = ❍ | `$x = $_POST['content']` |   |
| ● = v | `echo($v)` |   |
| x = ⊗($x_1$, …, $x_n$) | `$a = $t1 * $t2` |   |
| x = filter | `$a = htmlentities($t1)` |   |
| validate(v, $v_c$, $l_c$, $v_t$, $l_t$) | `if(is_num($t1)) {…}` |   |
| v ← ϕ ($v_1$, $v_2$) | `$v = phi($v1, $v2)` |   |

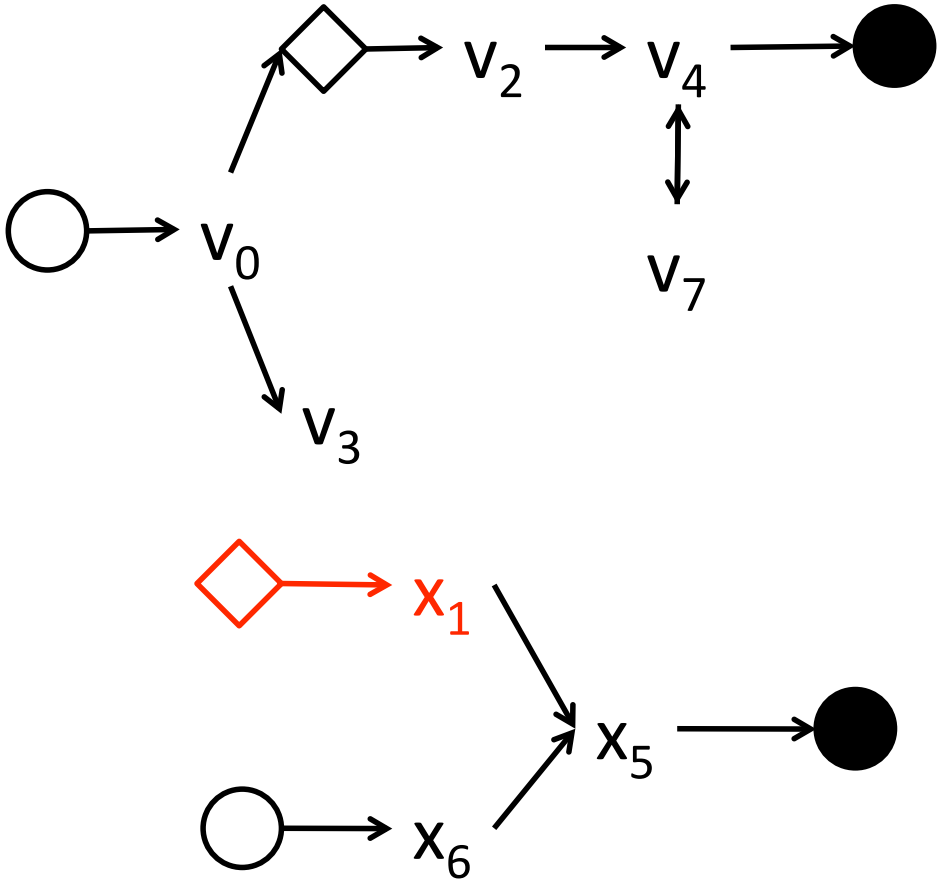
# Example of constraint graph



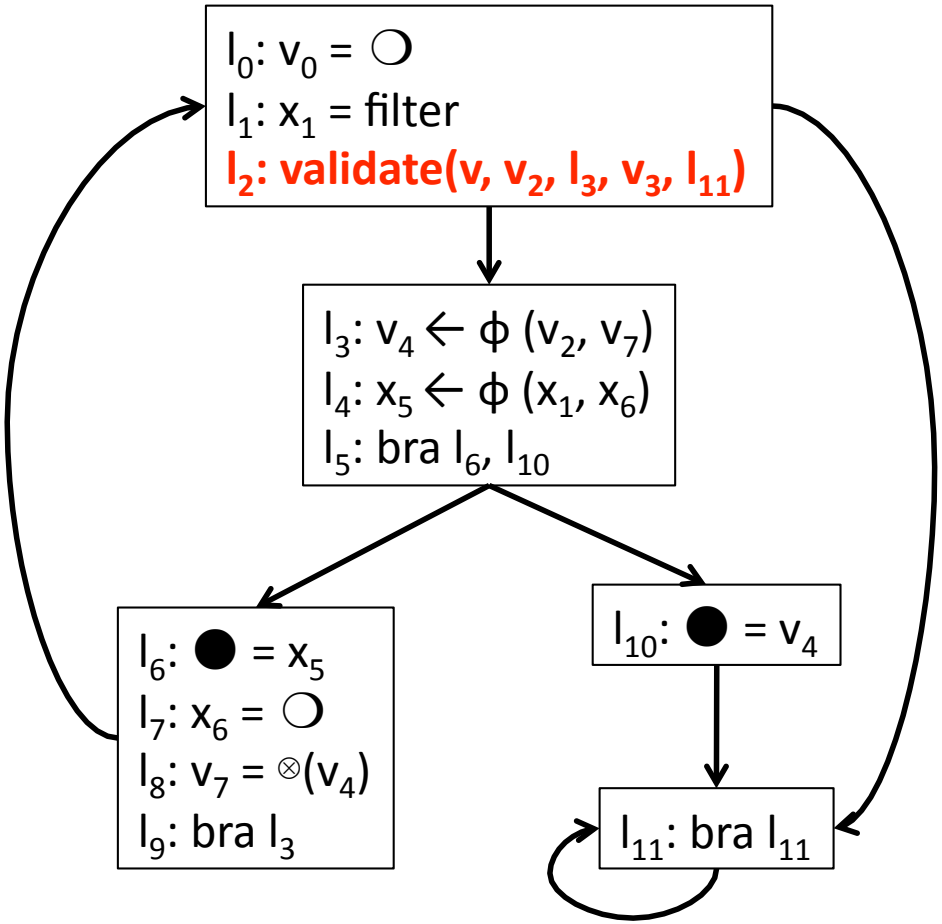



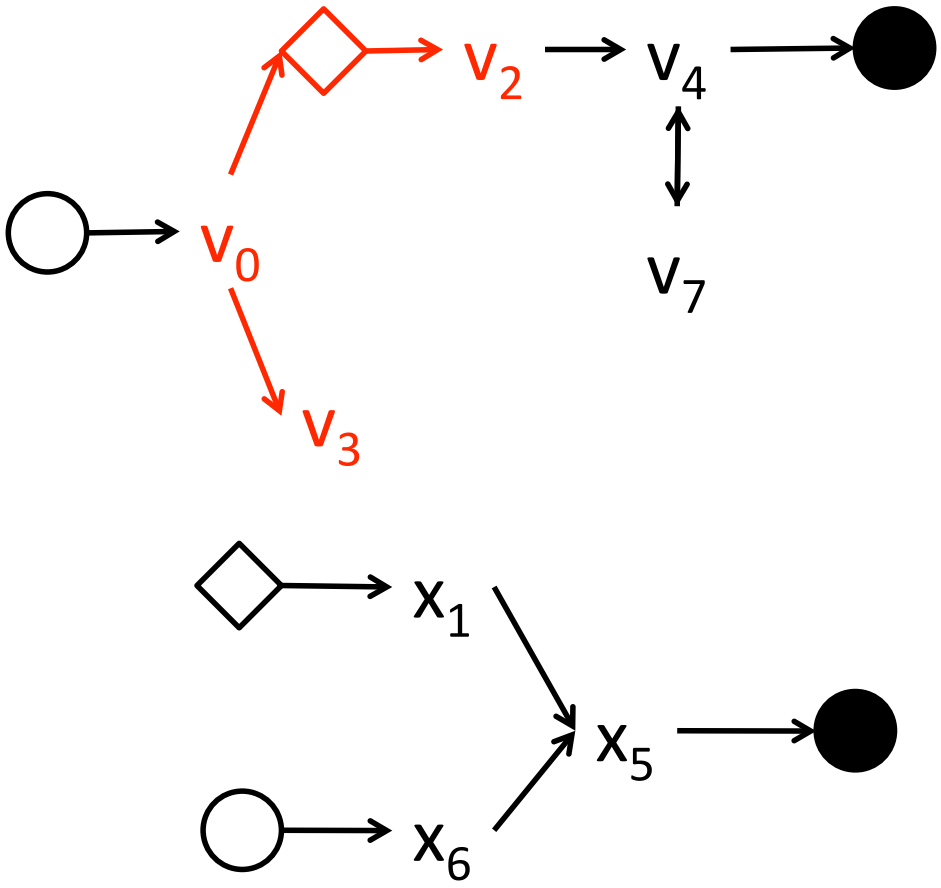
# Example of constraint graph



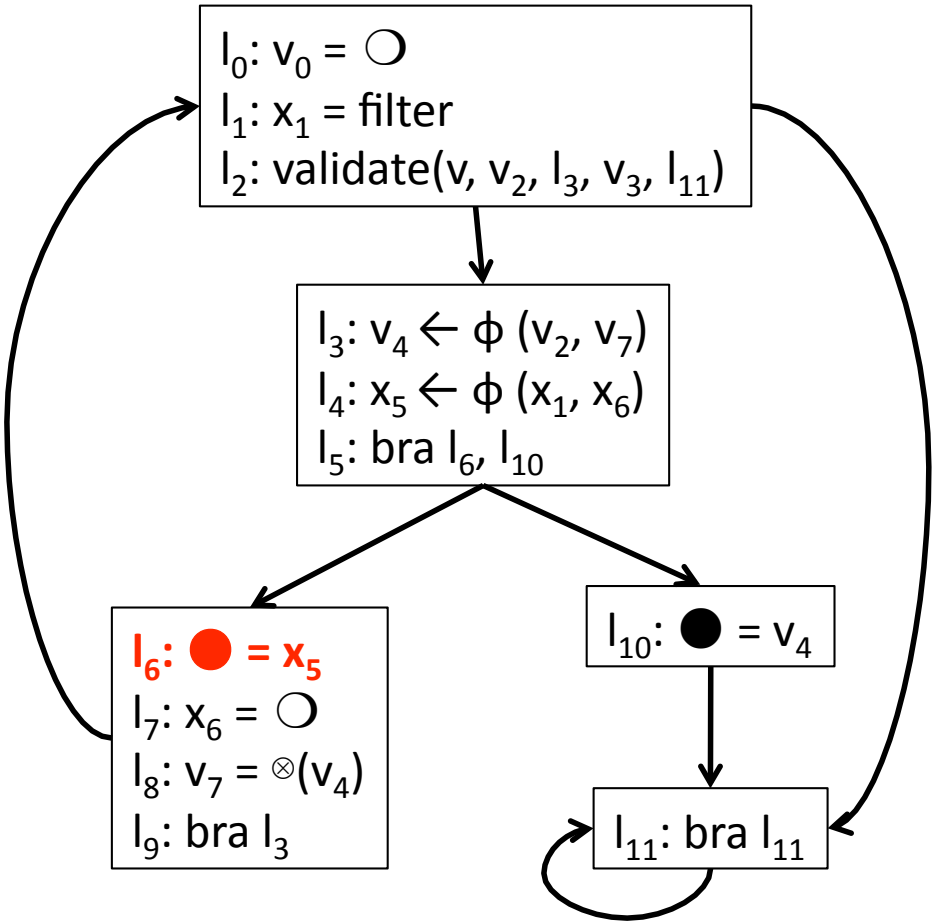



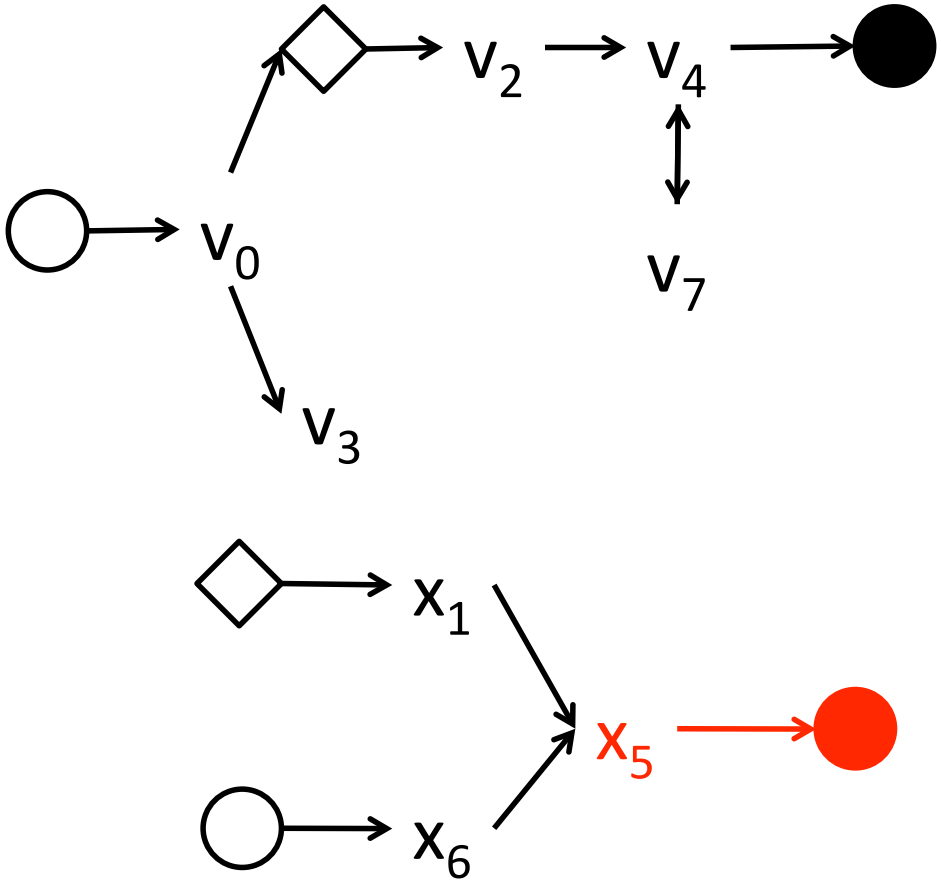
# Example of constraint graph



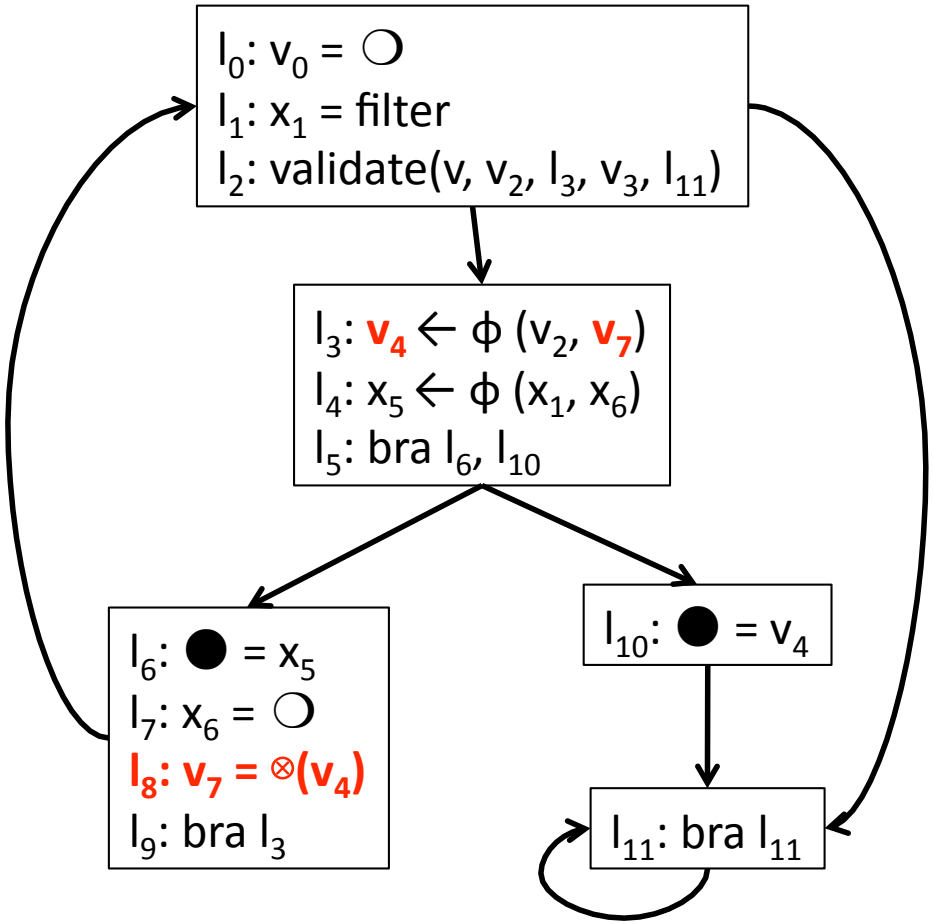



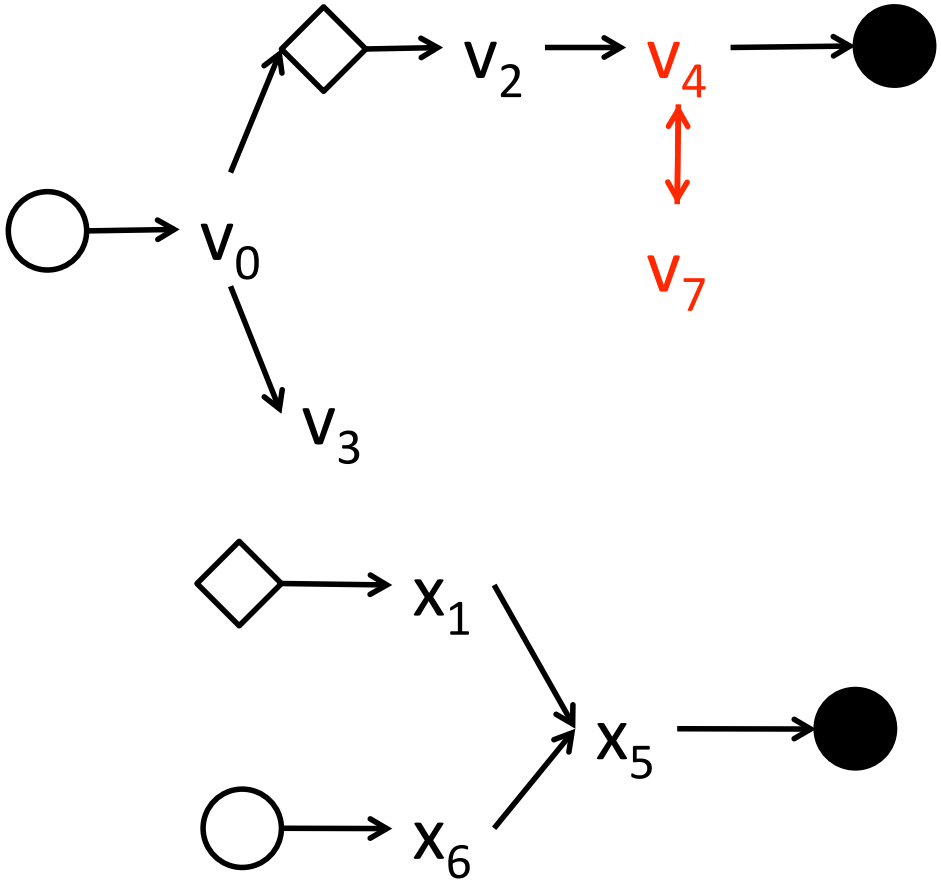
# Example of constraint graph



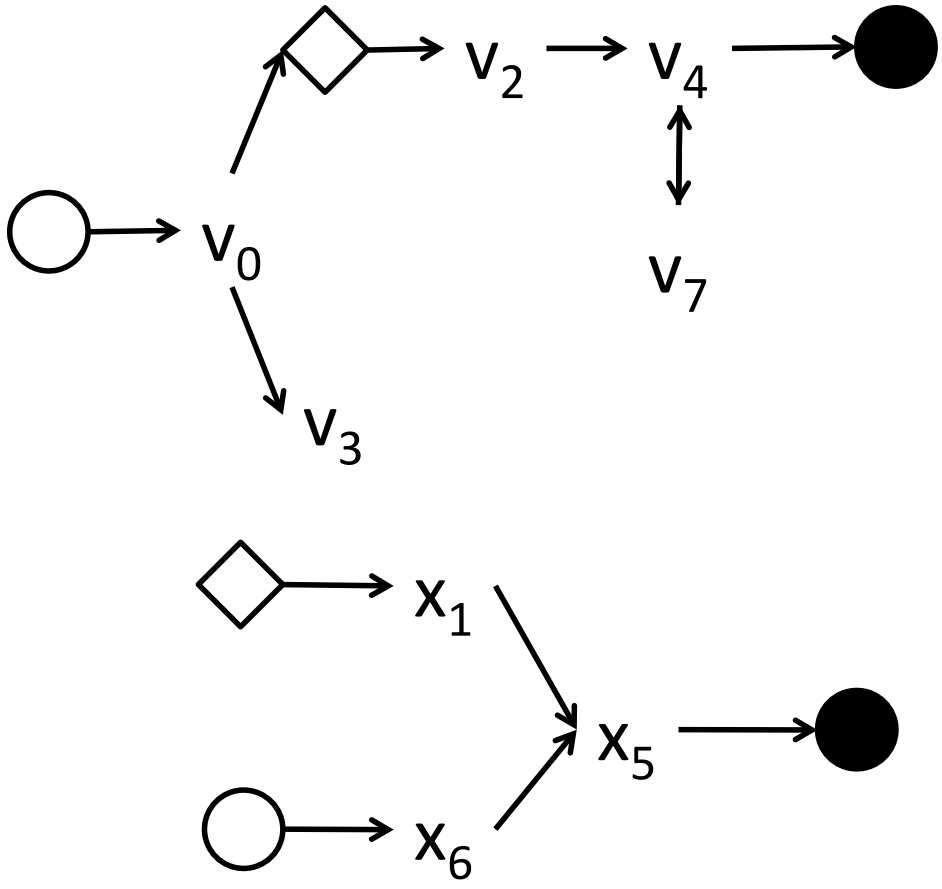
# Example of constraint graph



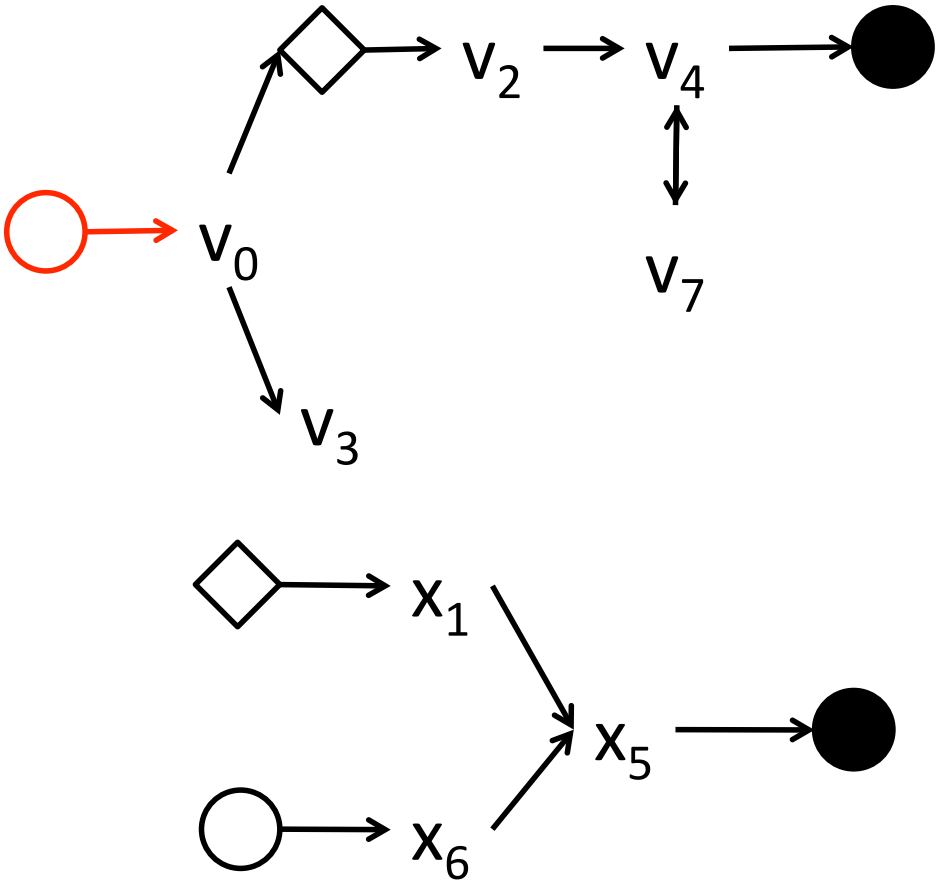
# Traverse the Constraint Graph

Find a path from ○ to ● without passing through ◇



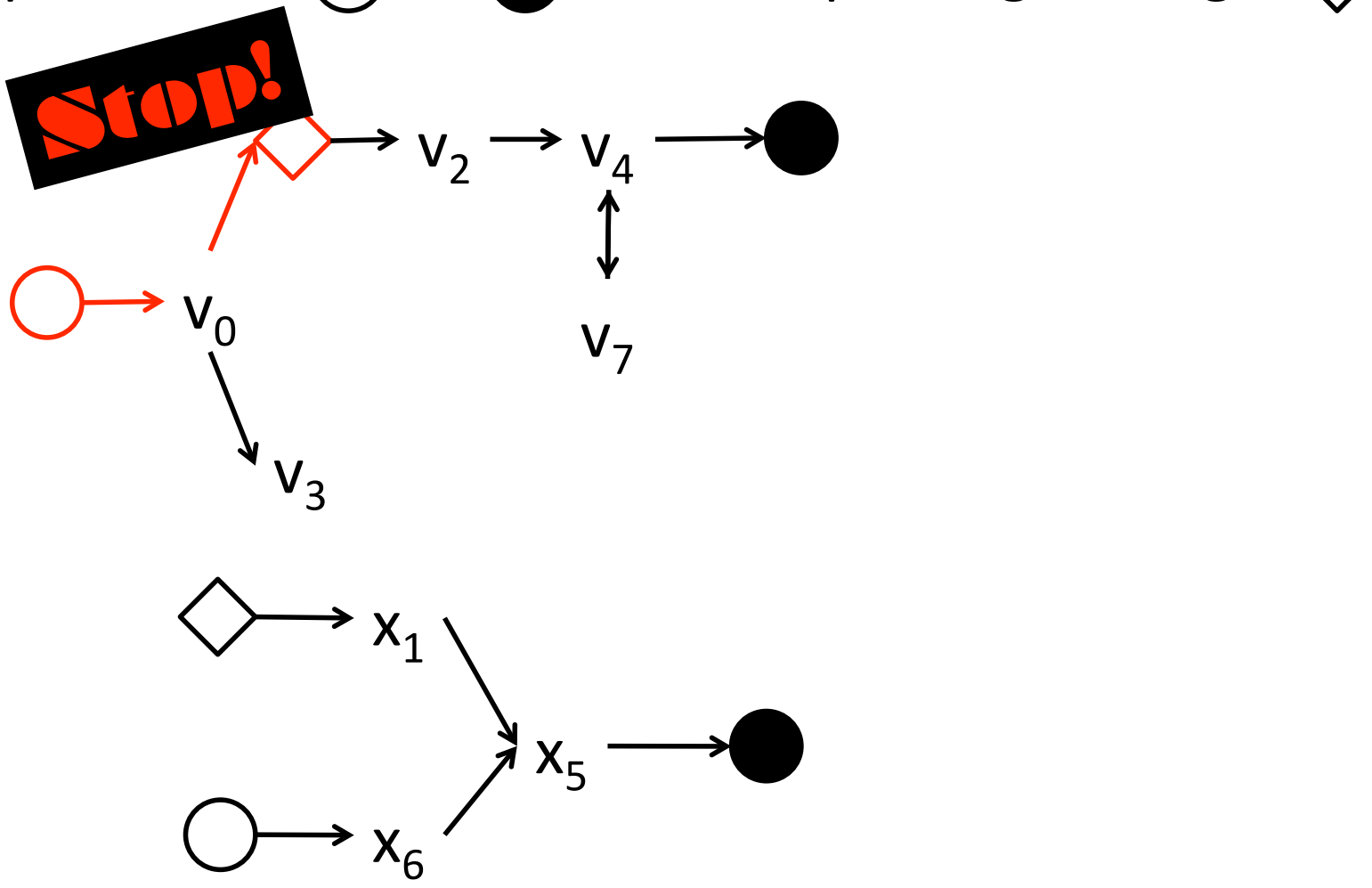
# Traverse the Constraint Graph

Find a path from ○ to ● without passing through ◇



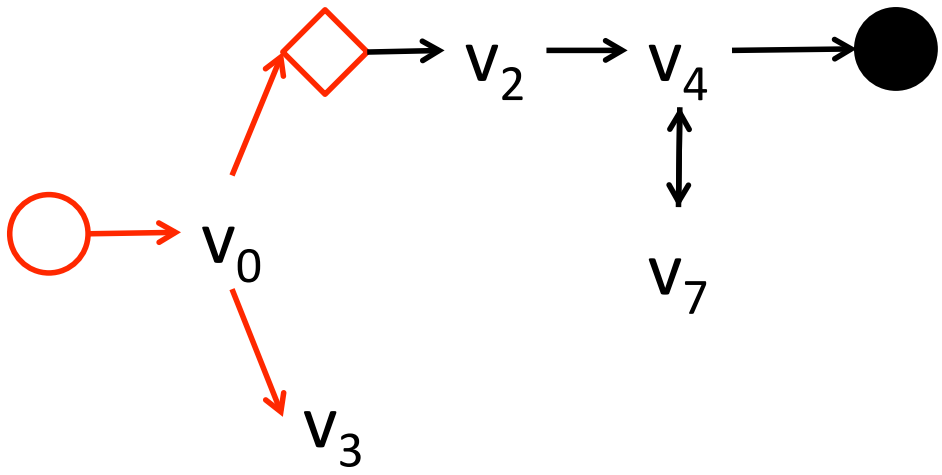
# Traverse the Constraint Graph

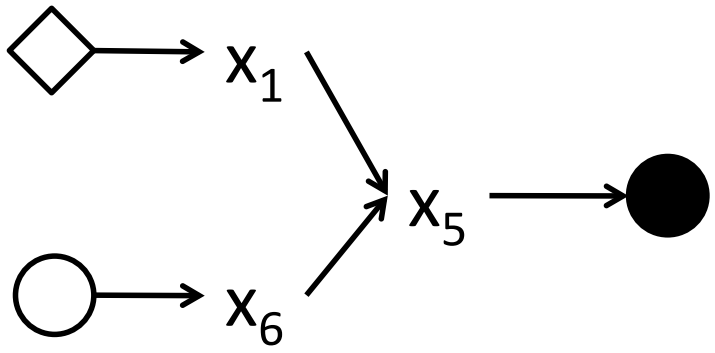
Find a path from ○ to ● without passing through ◇



# Traverse the Constraint Graph

Find a path from ○ to ● without passing through ◇



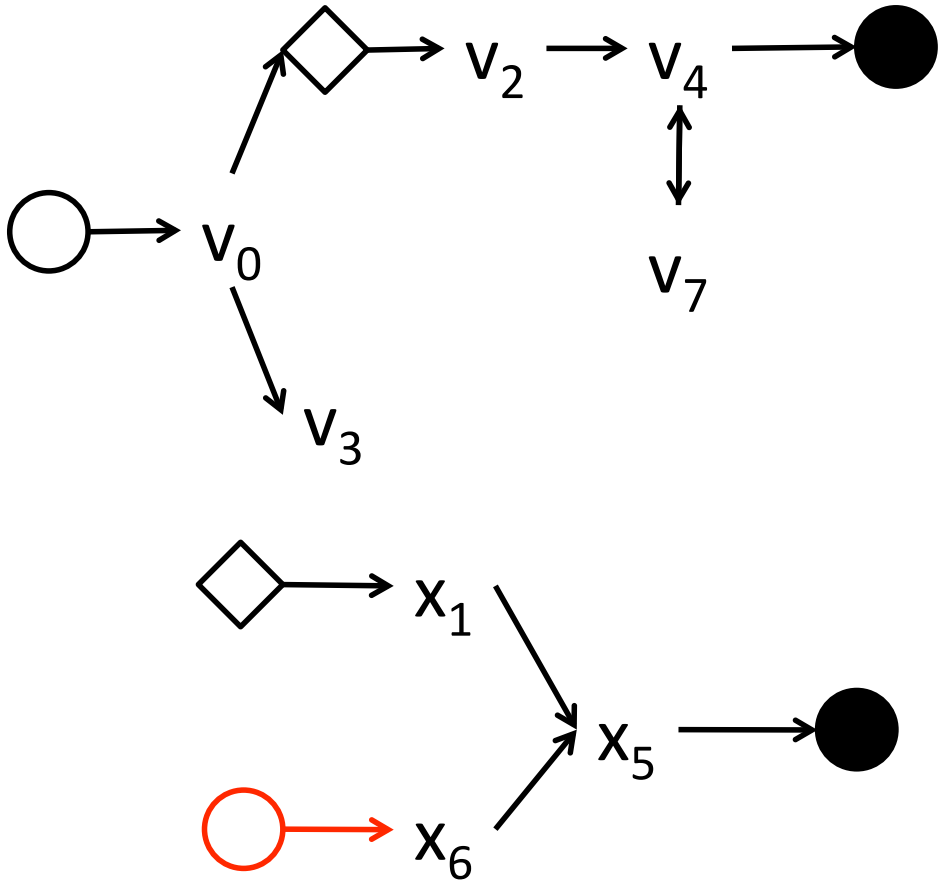




**Report:**

this program slice is bug free

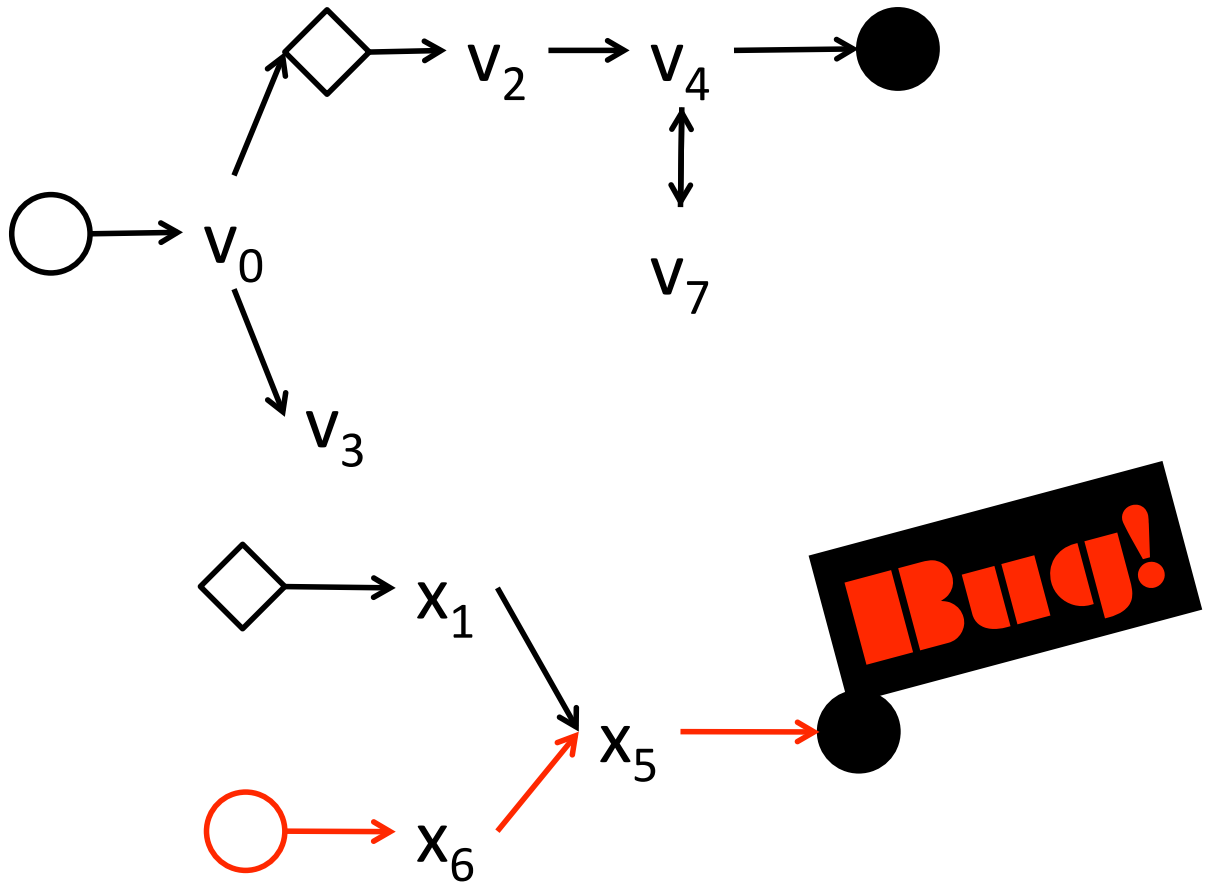
# Traverse the Constraint Graph

Find a path from ○ to ● without passing through ◇



# Traverse the Constraint Graph

Find a path from ○ to ● without passing through ◇



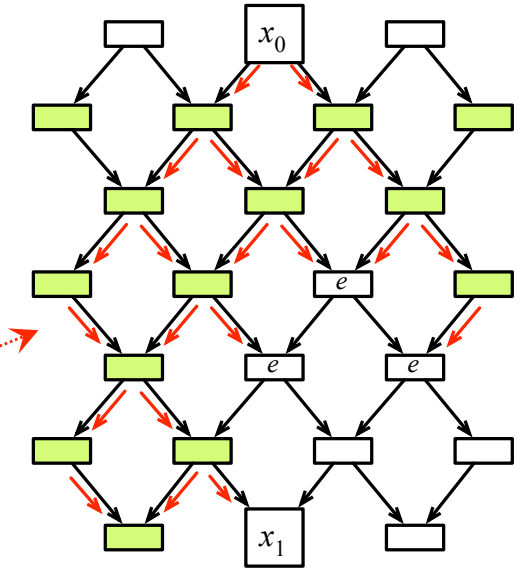
PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# Data Flow analysis as Graph Reachability

- This data flow analysis reduces to a simple graph reachability problem because the lattice that is associated with each variable has height two: either a variable is clean, or it is tainted.
- In our formalism, any direct dependence from a variable v to a variable u transmits the abstract state from u to v.
- Therefore, we just want to know if there is a path from a source of malicious information, the original tainted data, to sensitive operations.
  - This path must not cross sanitizers, because sanitizers propagate clean information.

# Program Slices

- Any subset of the dependence graph is called a *program slice*.
- The part of the dependence graph that depends on a variable $x_0$ is called the **forward slice** of $x_0$.
- The part of the dependence graph on which a variable $x_1$ depends on is called the **backward slice** of $x_1$.



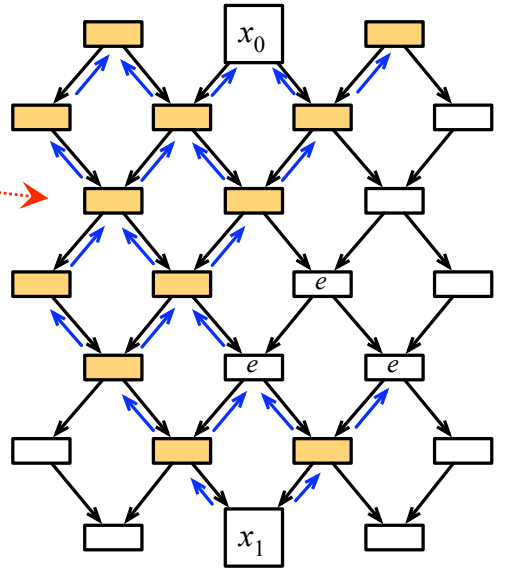
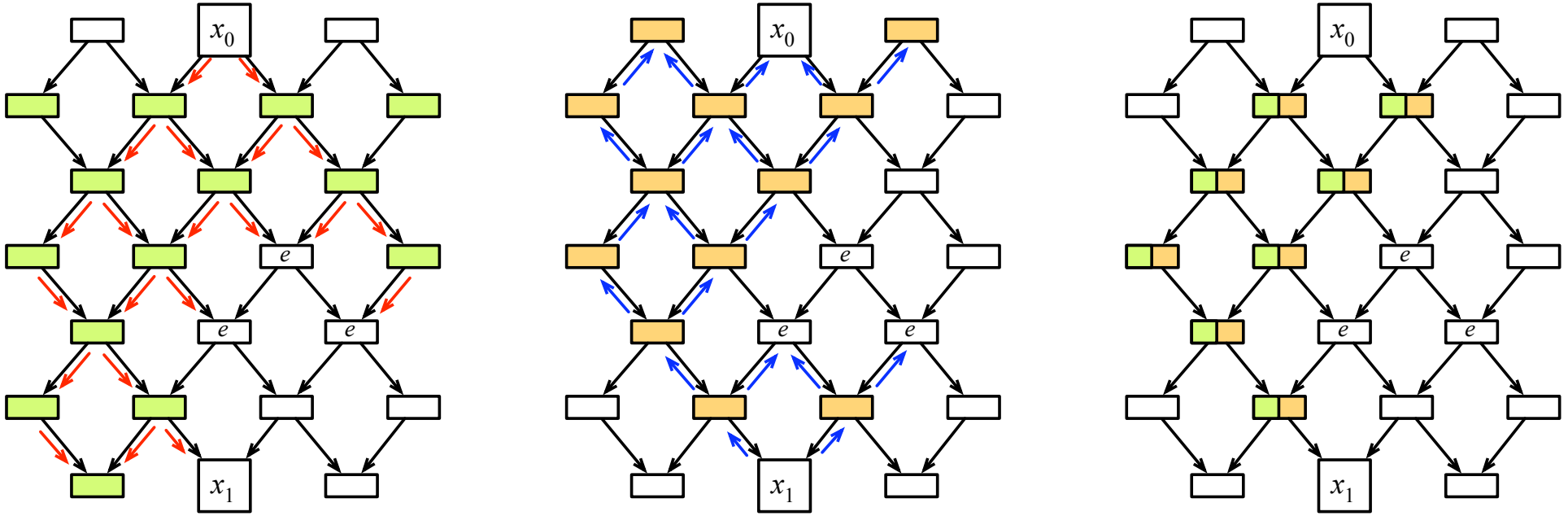




Image that you must report a "buggy" part of the program back to the user. How can you use this notion of slices to determine which part of the program is buggy?

# Program Slices

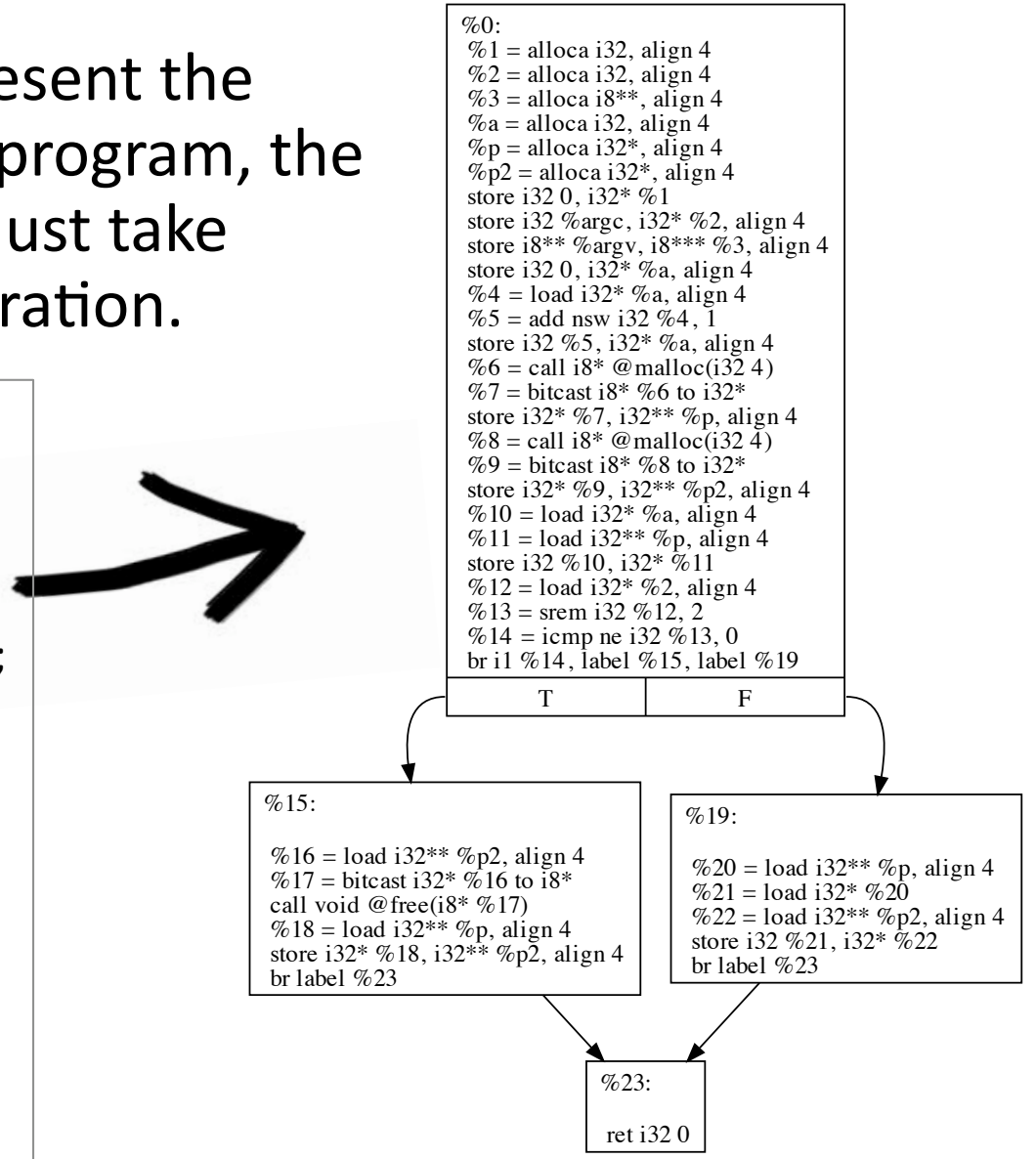
- Slices are useful to decrease the amount of information that we must report to the user, in case the program is vulnerable:
  - The dangerous part of the program is given by the intersection of the backward slice of a sink with the forward slice of a source, as long as there is a path from this source to this sink.



# The Importance of Pointer Analysis

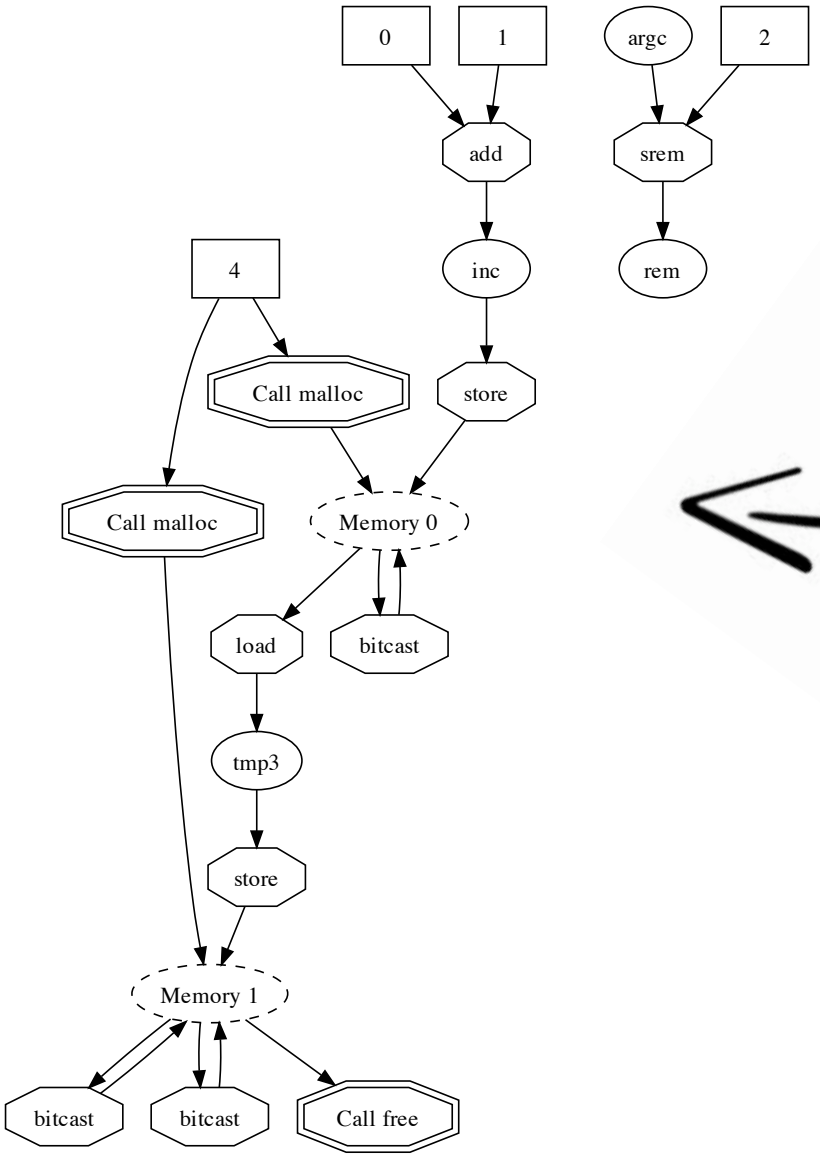
- In order to truly represent the dependencies in the program, the dependence graph must take pointers into consideration.

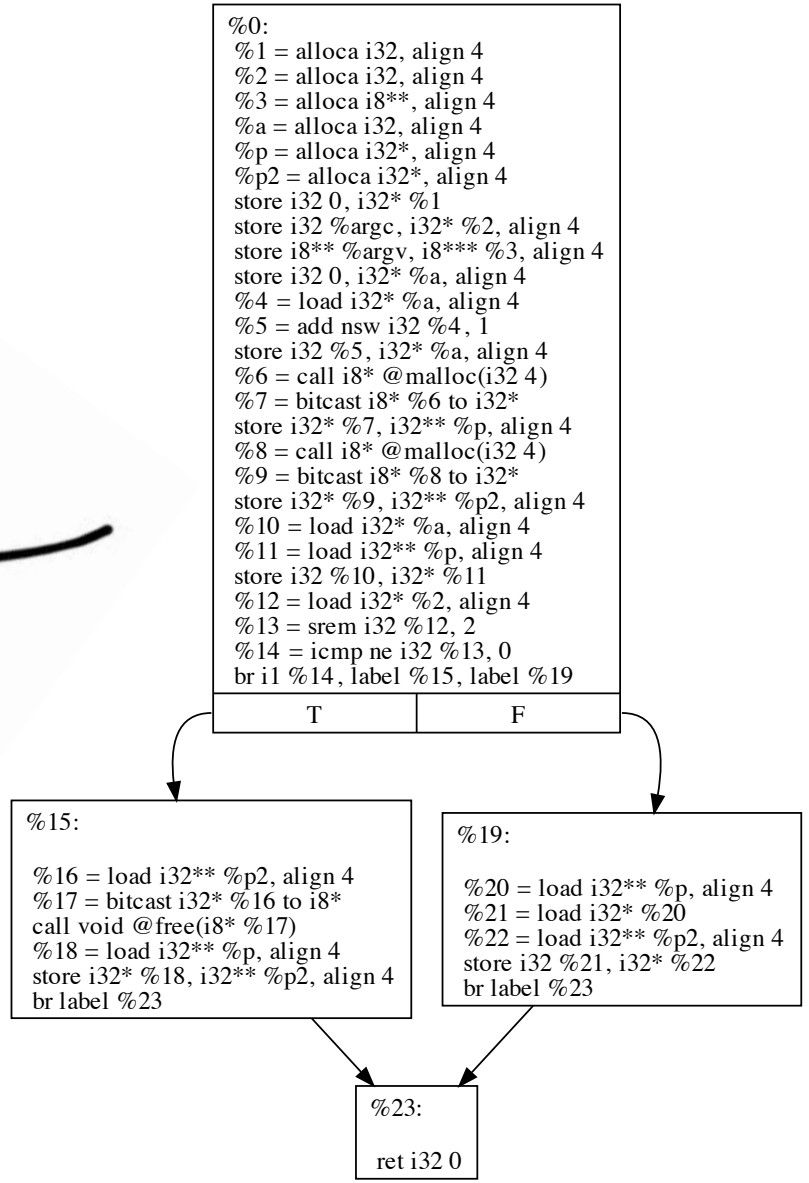
```
int main(int argc, char** argv){
  int a = 0;
  a++;
  int* p = (int*)malloc(sizeof(int));
  int* p2 = (int*)malloc(sizeof(int));
  *p = a;
  if (argc%2) {
    free(p2);
    p2 = p;
  } else {
    *p2 = *p;
  }
  return 0;
}
```




This example is taken from an actual LLVM bytecode.

# The Importance of Pointer Analysis




This example is taken from an actual LLVM bytecode.

# Real World Example

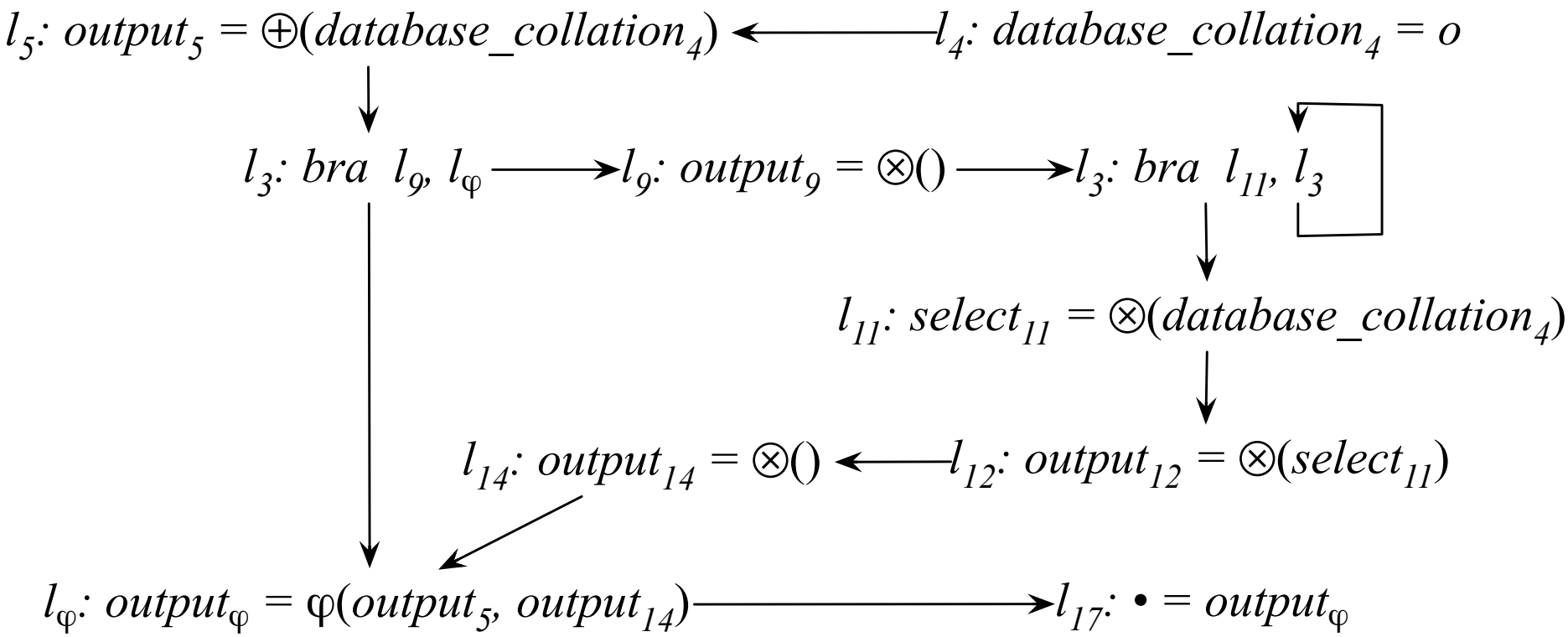
```
<?php
$host = $_POST['host'];       $uid = $_POST['uid'];       $pwd = $_POST['pwd'];
$database_collation = $_POST['database_collation'];
$output = '<select id="database_collation" name="database_collation”> <option
value="'.$database_collation.'" selected >’.$database_collation.'</option></
select>';
if ($conn = @ mysql_connect($host, $uid, $pwd)) {
   $getCol = mysql_query("SHOW COLLATION");
   if (@mysql_num_rows($getCol) > 0) {
      $output = '<select id="database_collationse_collation”
                        name="database_collation">';
      while ($row = mysql_fetch_row($getCol)) {
         $selected = ( $row[0]==$database_collation ? ' selected' : '' );
         $output .= '<option value="'.$row[0].'"'.$selected.'>'.$row[0].'</option>';
      }
      $output .= '</select>';
   }
}
echo $output;
?>
```

Can you identify the vulnerability of this program?

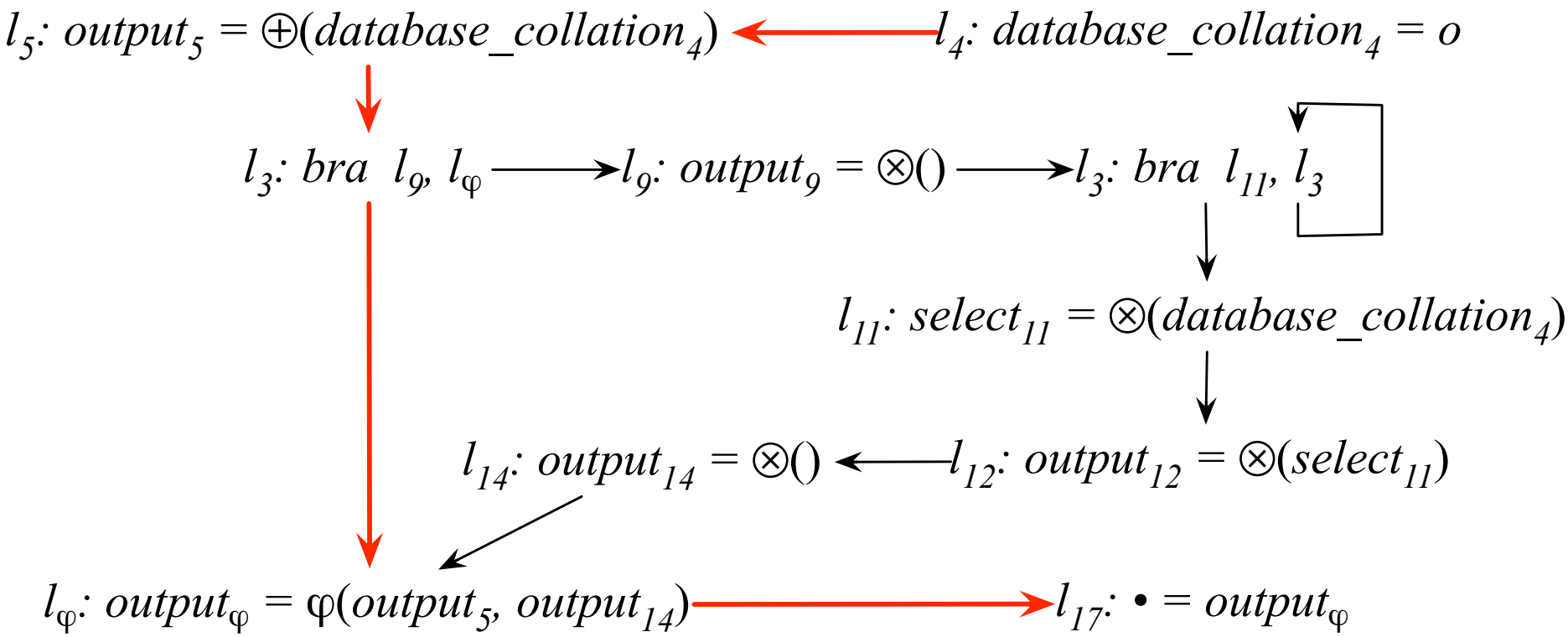
MODx CMS version 1.0.3

# Real World Example

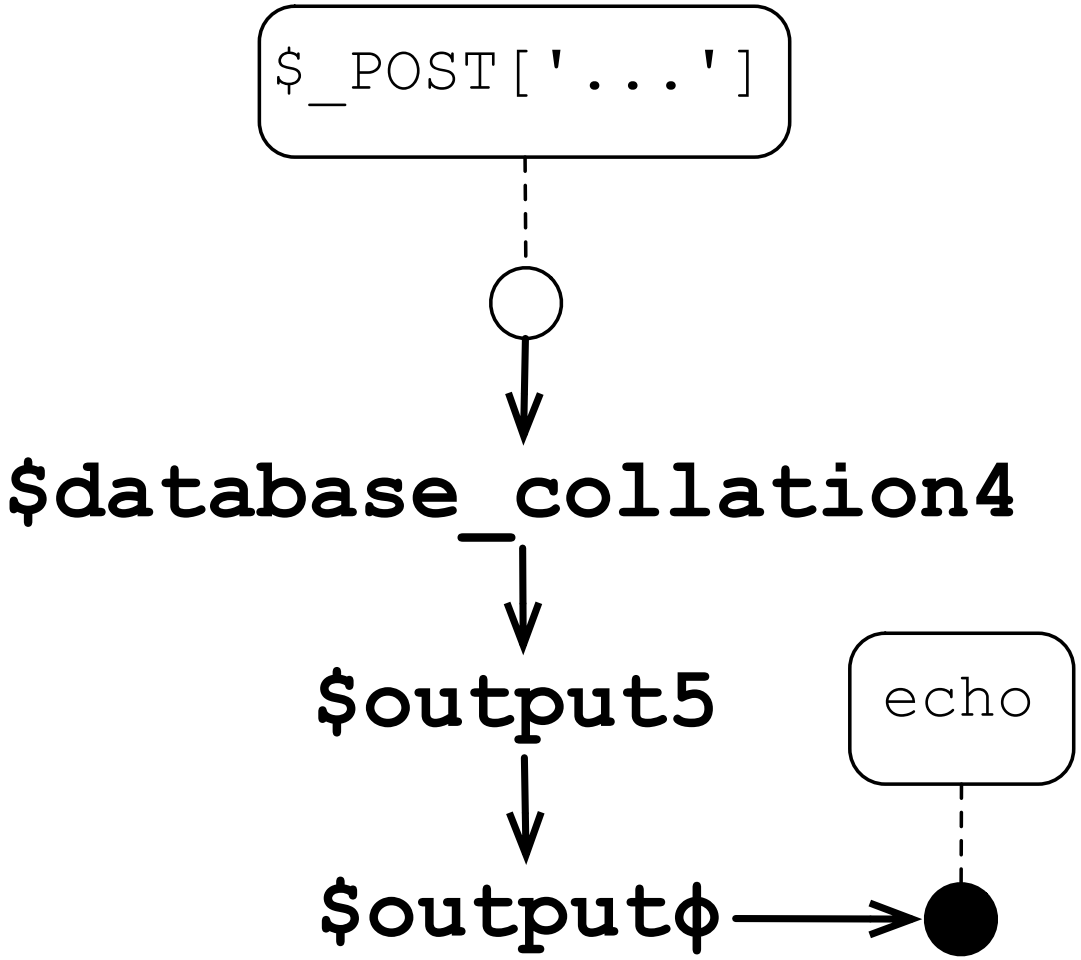
Where is the bug?



# Real World Example



# Real World Example



PPGCC
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO DCC-UFMG

# A Bit of History

- The foundations of information flow were introduced by Denning and Denning in 1977
- The notion of program slice was introduced by Weiser.
- The dense algorithm that we saw in these slides is an adaptation of Orbaek and Palsberg's analysis.
- These slides follow the exposition given by Rimsa *et al*.


- Denning, D., and Denning, P., "Certification of programs for secure information flow", commun. ACM 20 p 504-513 (1977)
- Weiser, M., "Program Slicing", ICSE, p 439-449 (1981)
- Orbaek, P., and Palsberg, J., "Trust in the lambda-calculus", Journal of Func. Programming 7(6), p 557-591 (1997)
- Rimsa, A., Amorim, M., and Pereira, F., "Tainted Flow Analysis on e-SSA-form Programs", CC, p 124-143 (2011)