From Qualitative to Quantitative Program Analysis: Permissive Enforcement of Secure Information Flow

Mounir Assaf

Software Security Lab, CEA LIST, Saclay
CIDre, Inria/Irisa/CentraleSupélec, Rennes

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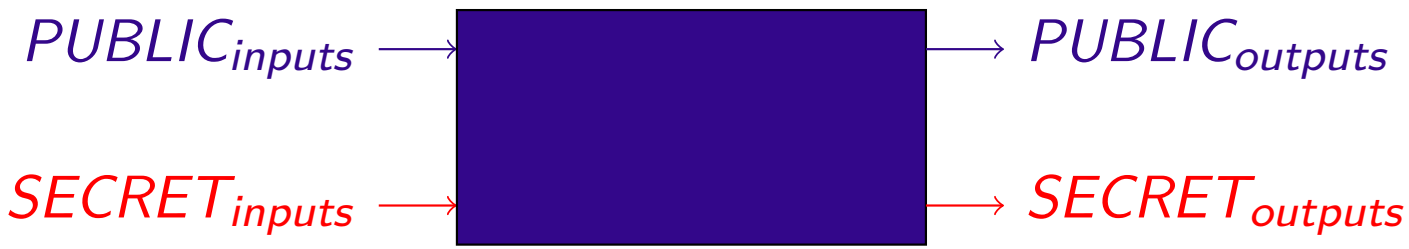
- Information security :
  - Confidentiality
  - Integrity
  - Availability
- Traditionally, dissemination of information is prevented through Access control :
  - Deals with what piece of information can be accessed? by whom?
  - Yet, is this piece of information handled correctly when accessed?
- Information Flow Control :
  - Tracks how information is propagated through a program
  - Verifies that **information flows** are secure with respect to a security policy

- Attacker model :
  - They know the source of programs and public outputs
  - They control public inputs



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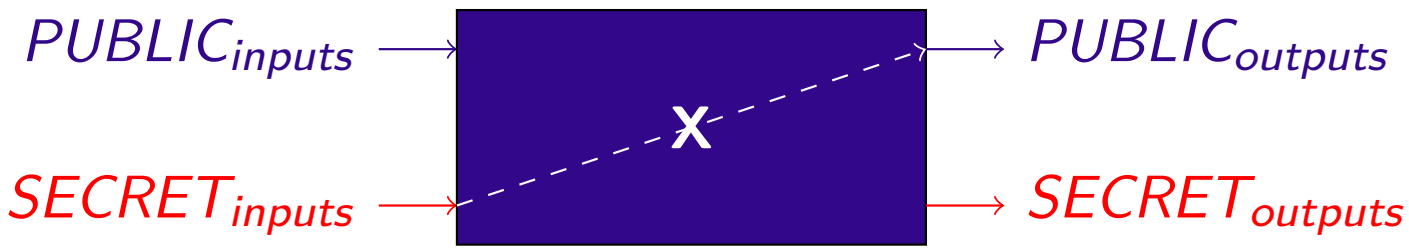
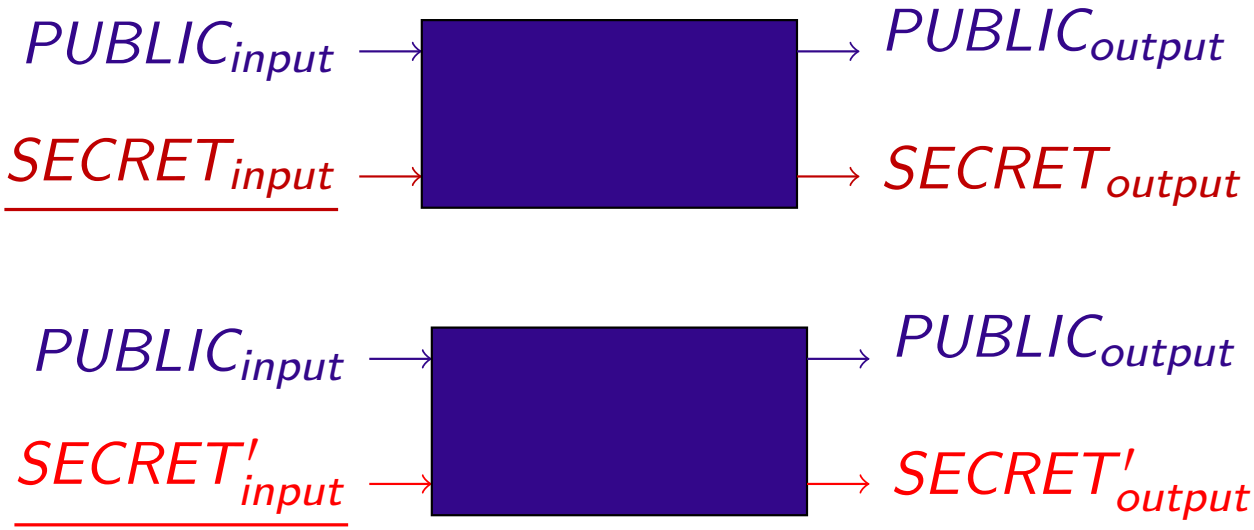


- A program is secure if non-interfering
  - Roughly, **non-interference** (in the case of confidentiality) is **independance of public outputs from secret inputs**

- **Termination-Insensitive Non-Interference** (TINI)
  - Two **terminating executions** which differ only on secret inputs deliver the same public outputs



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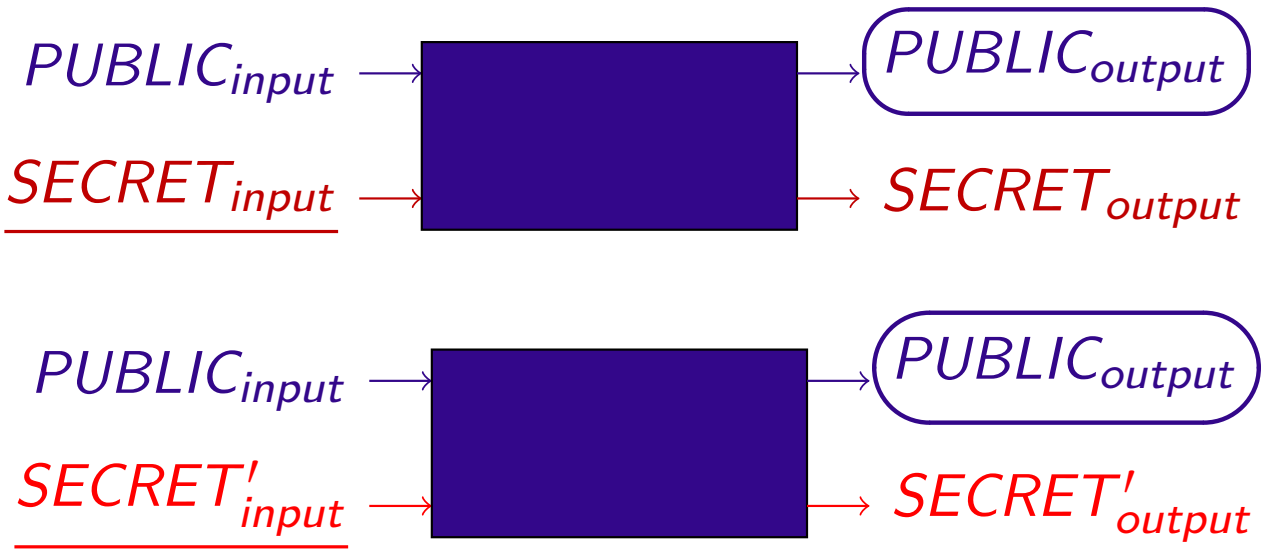


Explicit flows

- produced when information is transfered directly from source to destination

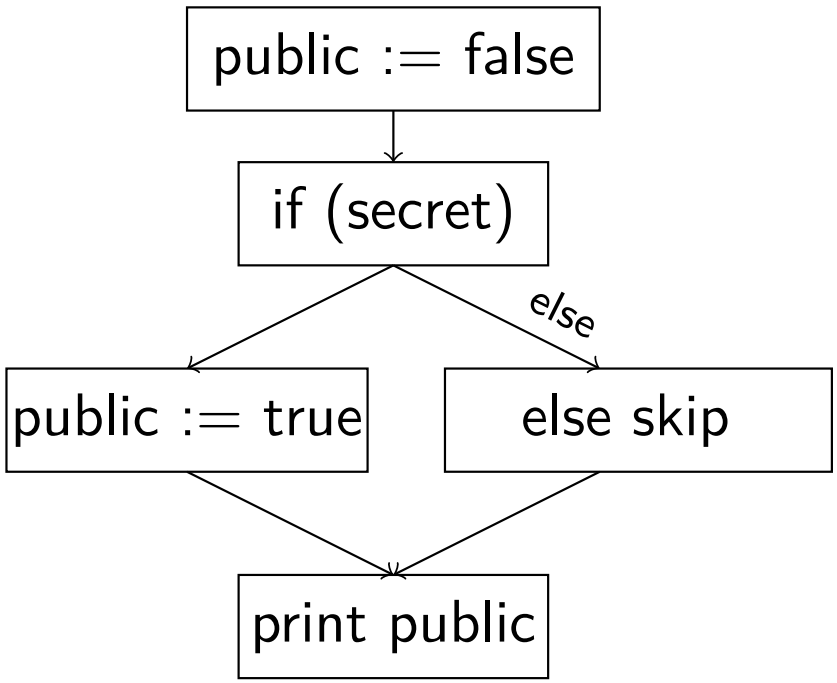
destination := source

Assignments generate explicit flows

- Explicit flow from variable `source` to `destination`

Implicit flows

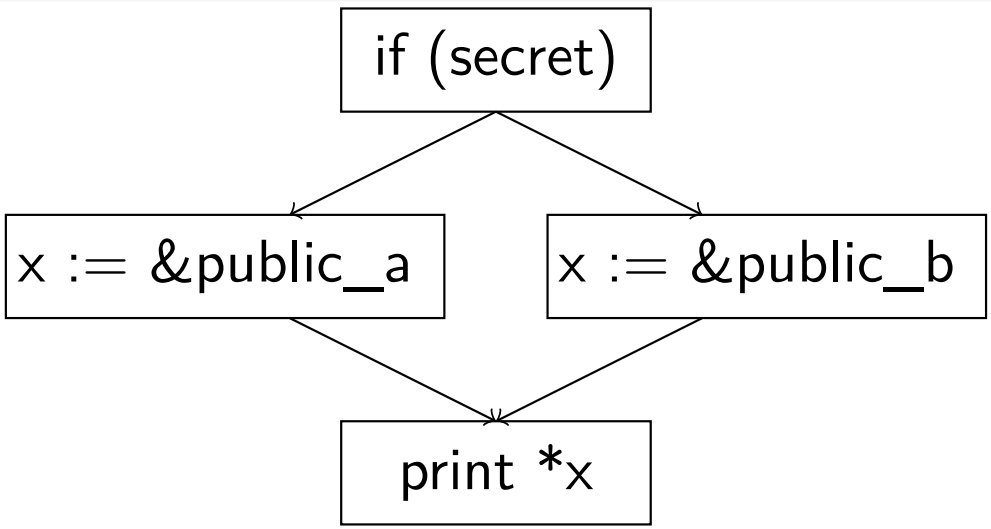
- produced when an assignment is conditioned on the value of an expression



- Implicit flow from variable `secret` to variable `public`

Pointer-induced flows

- produced whenever a pointer is dereferenced



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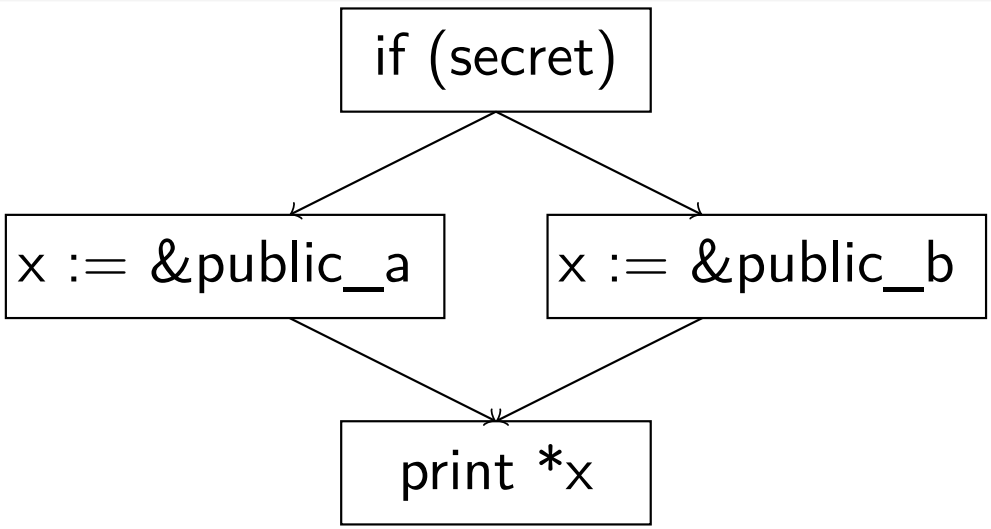

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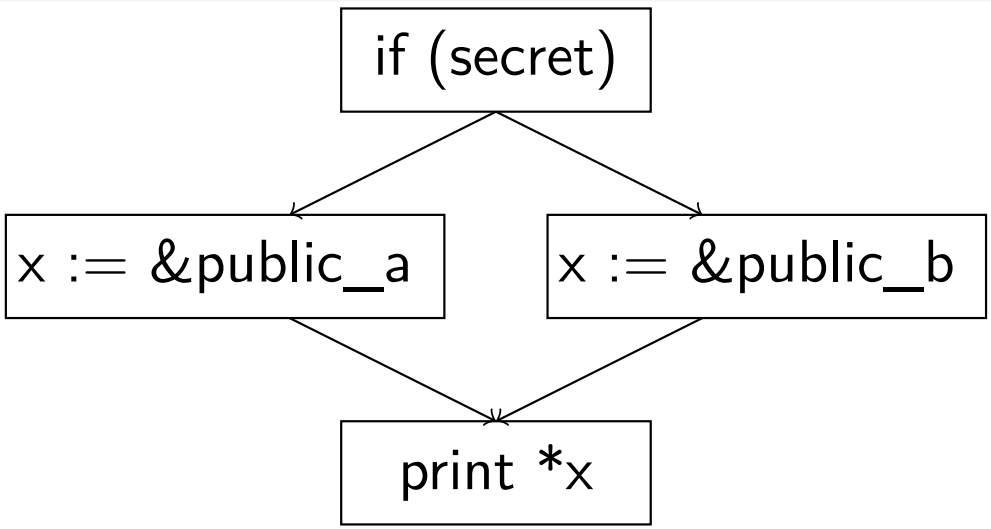

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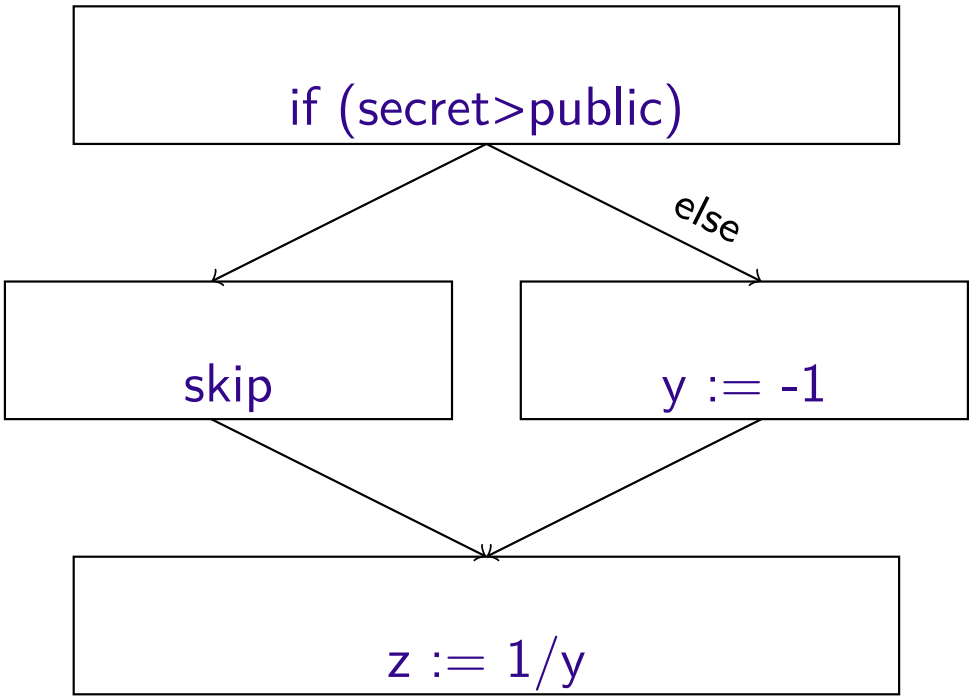
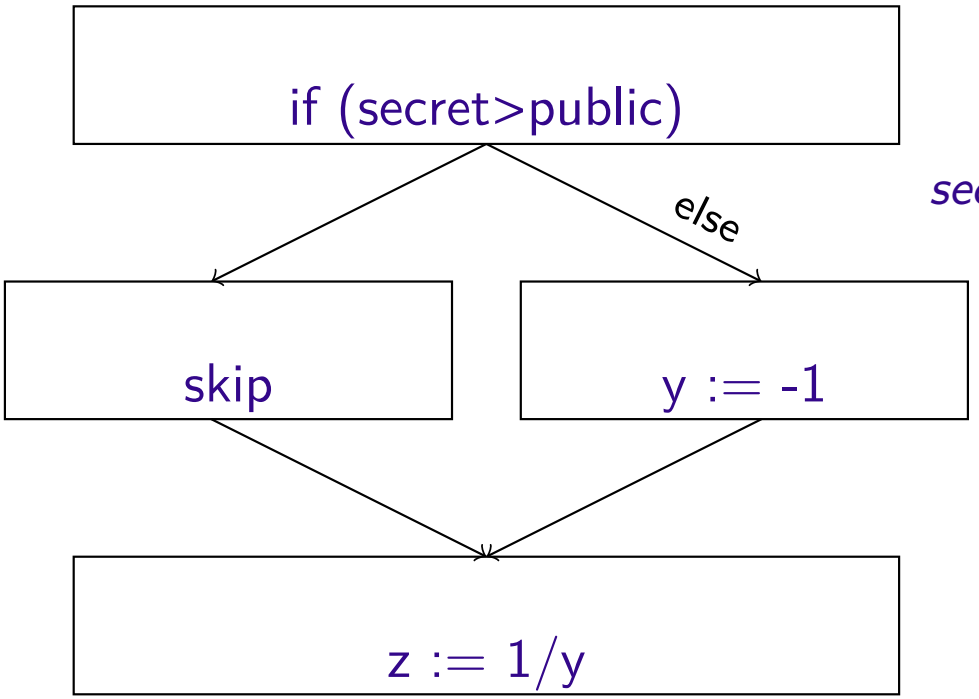


- Frama-C, an industrial-quality framework for source code analysis of C [Kirchner et al.,2015]
- Value Analysis plug-in
  - a tool based on Abstract Interpretation [Cousot & Cousot,77]
  - over-approximating the variation domains of variables
  - aimed at the detection of runtime errors



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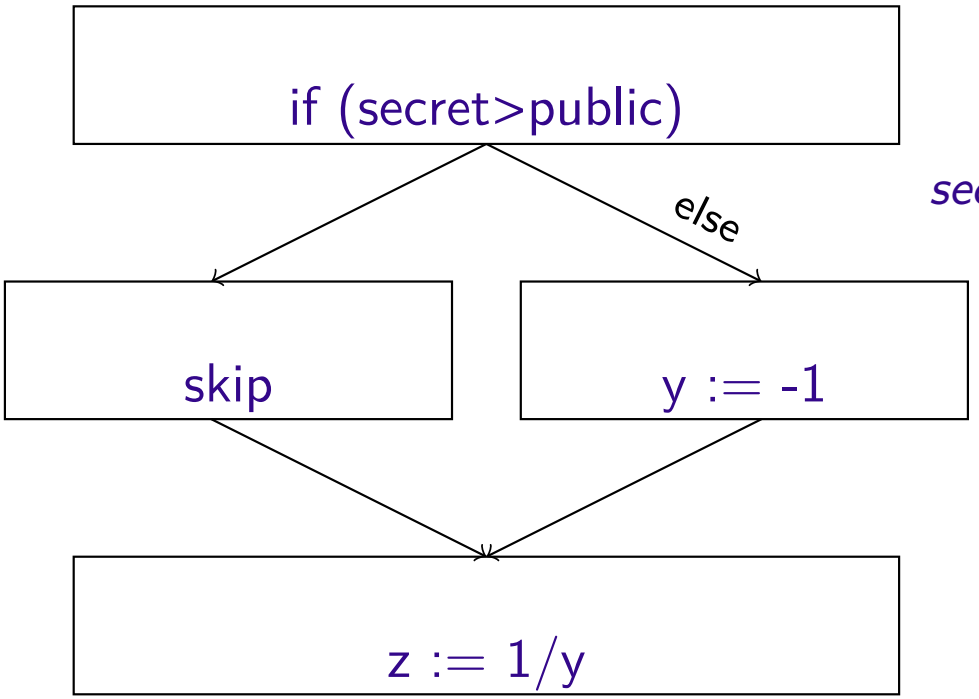

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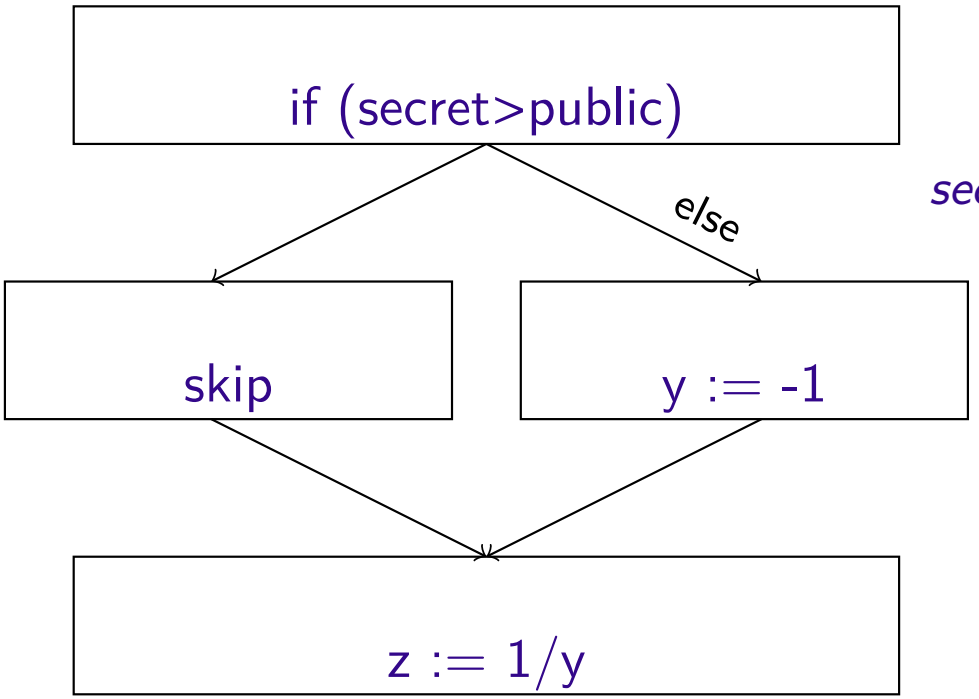

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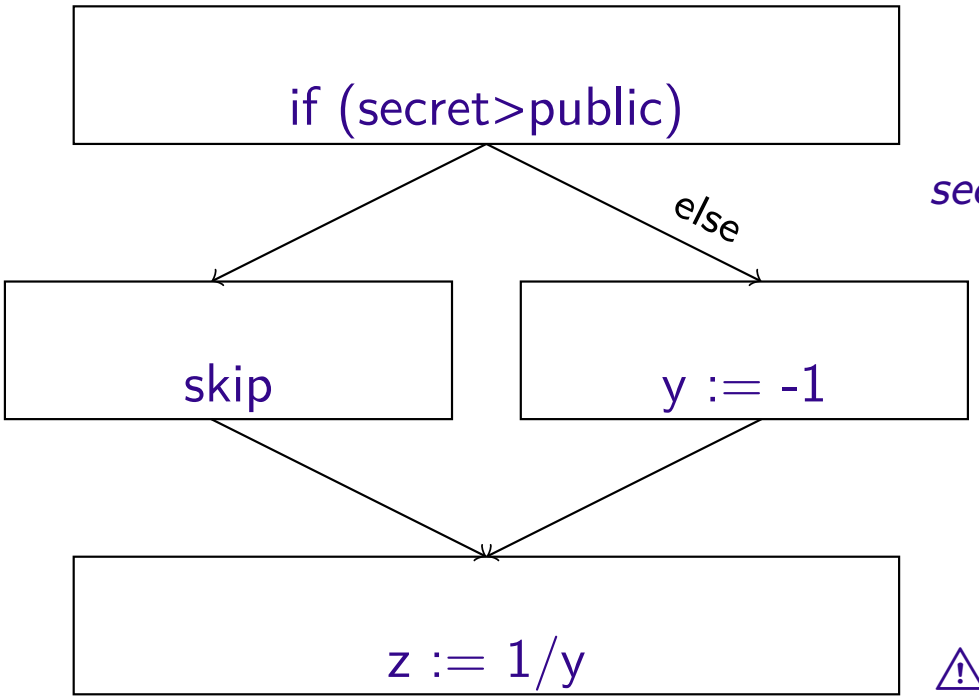

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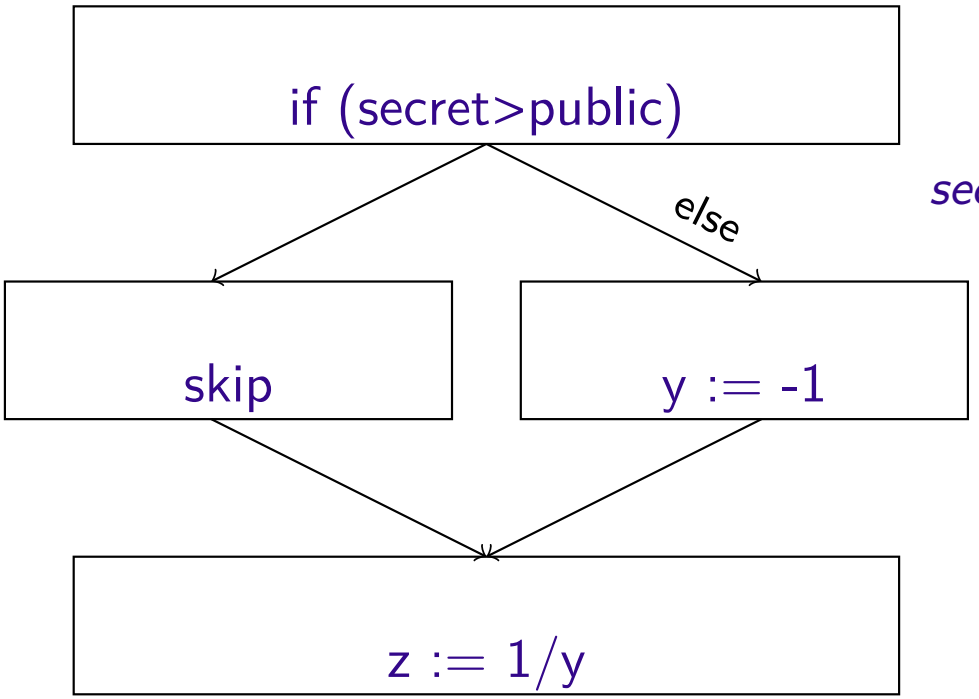

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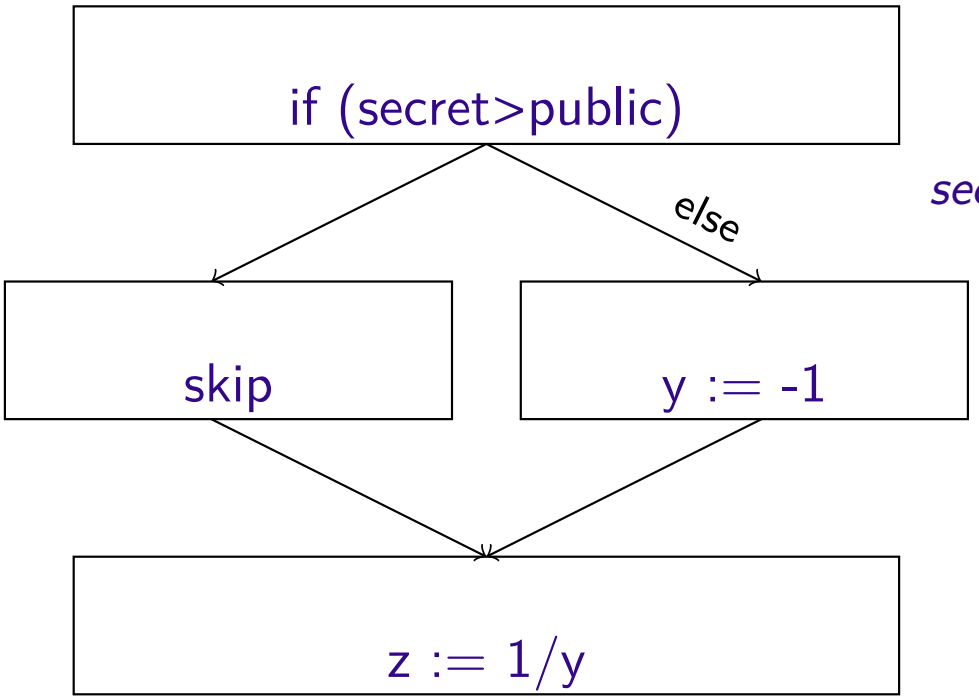
  - In a nutshell, simulating a partition of executions
  - Gaining precision by keeping both states separate



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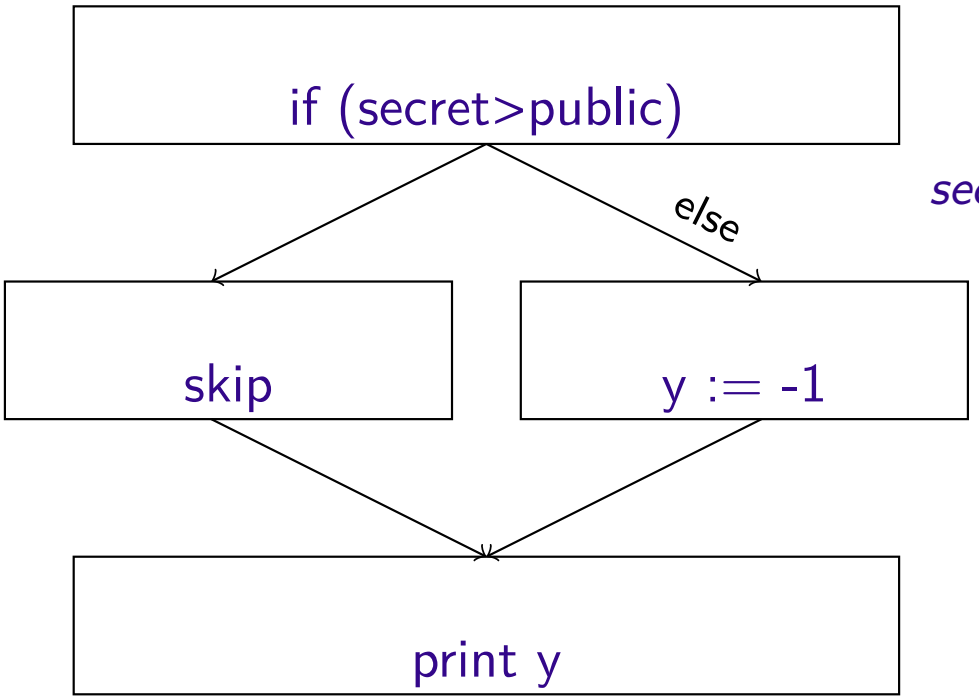

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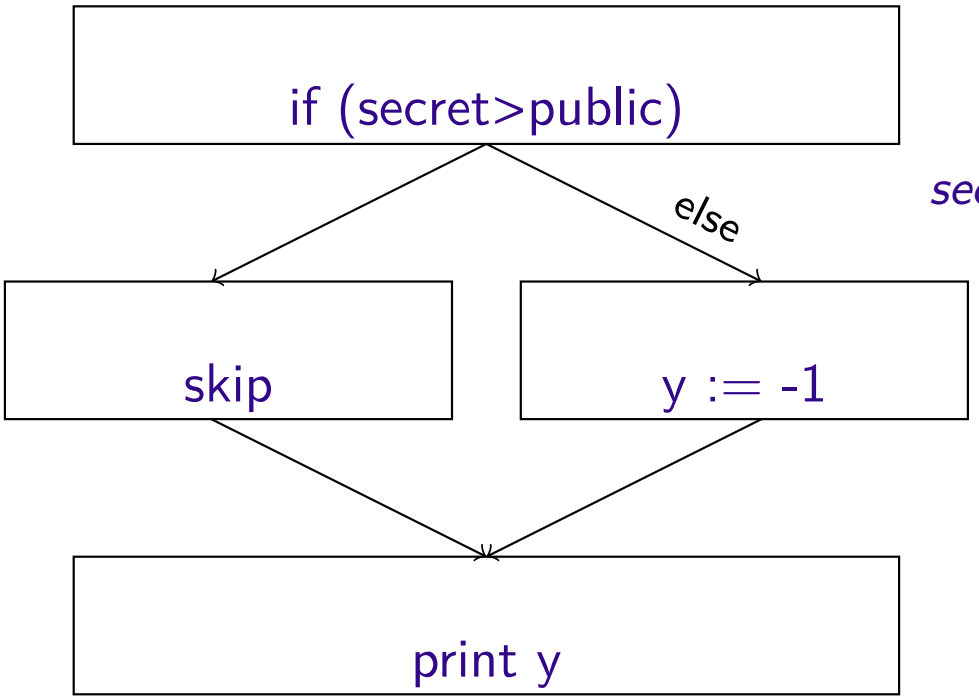

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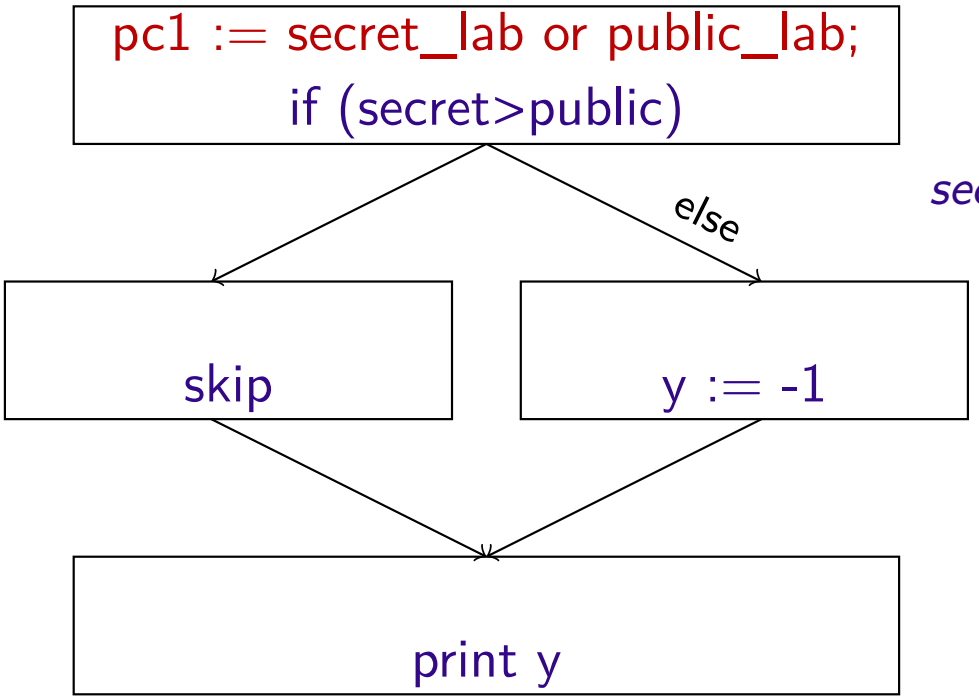

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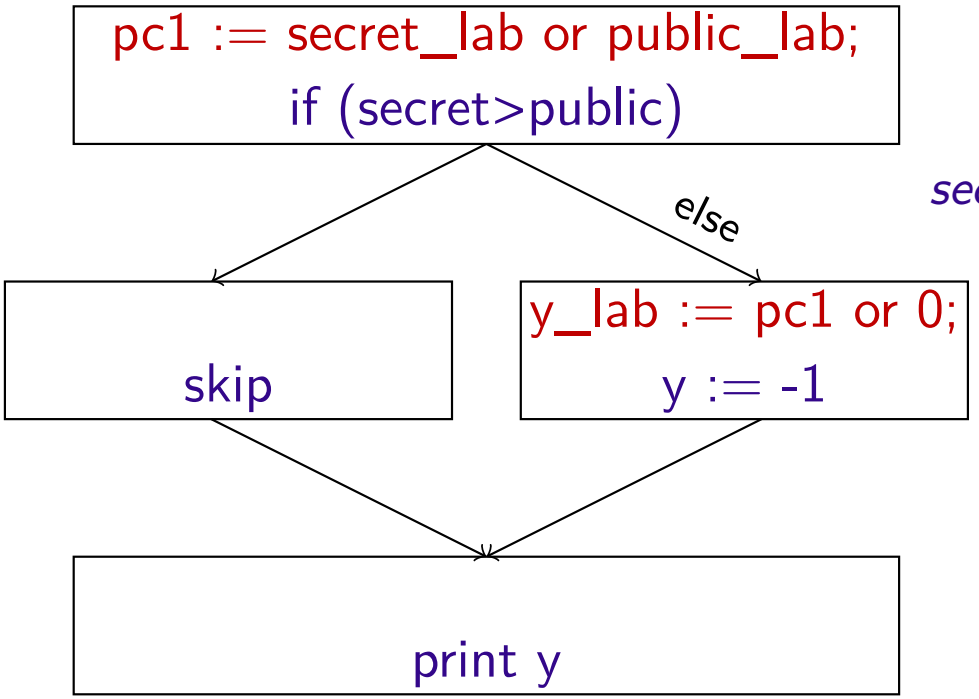

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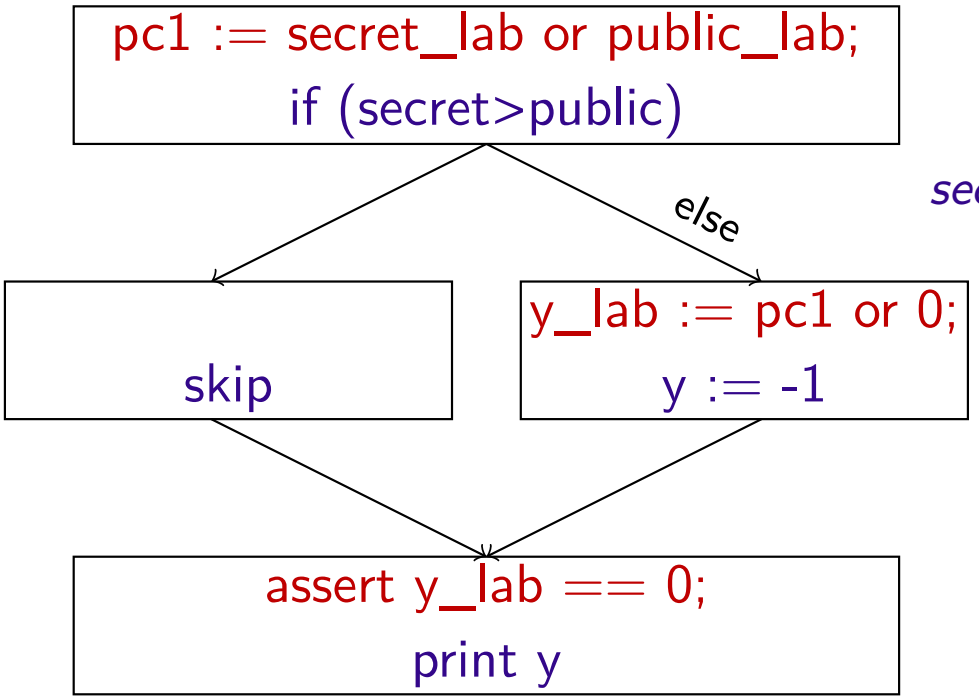

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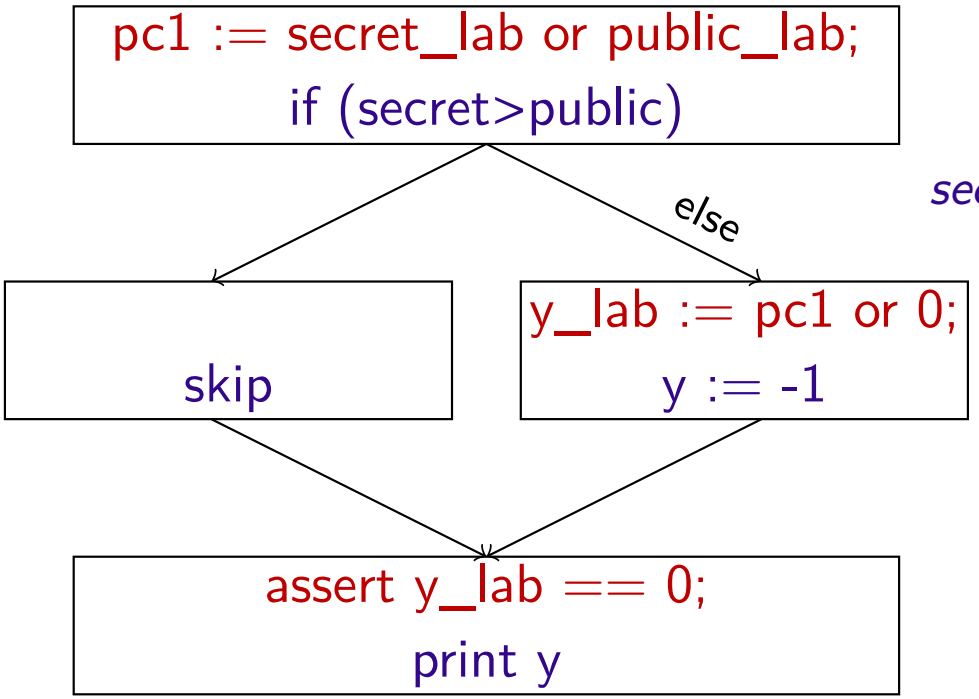

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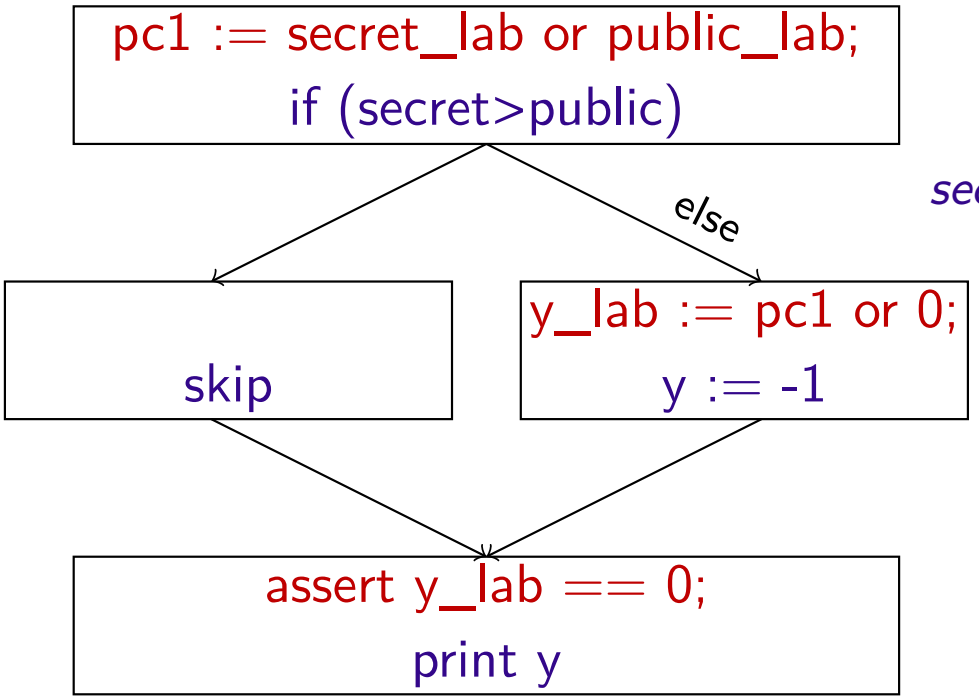

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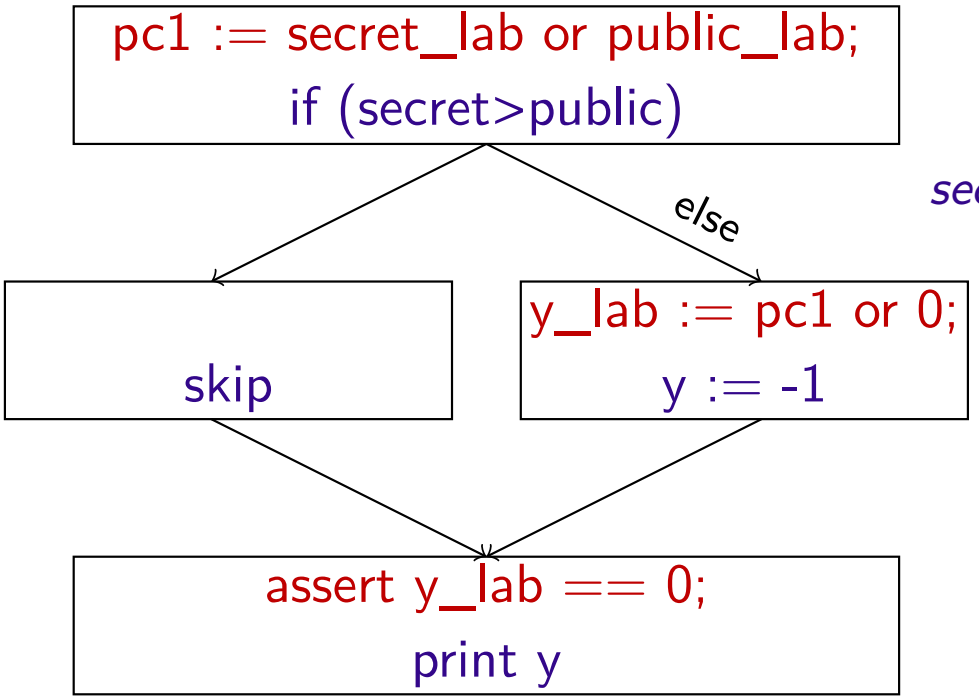

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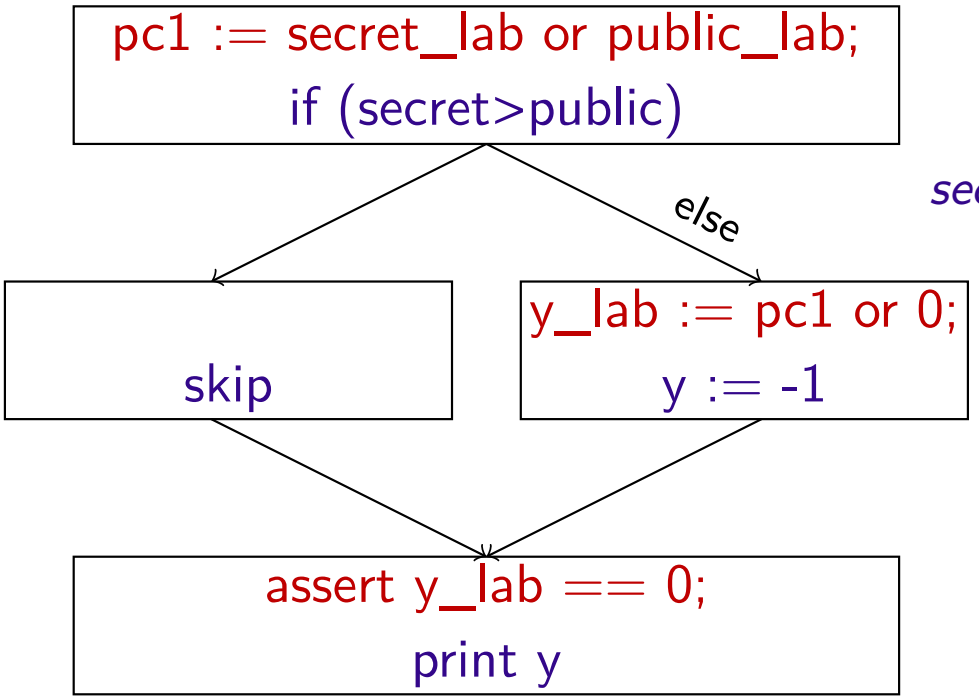

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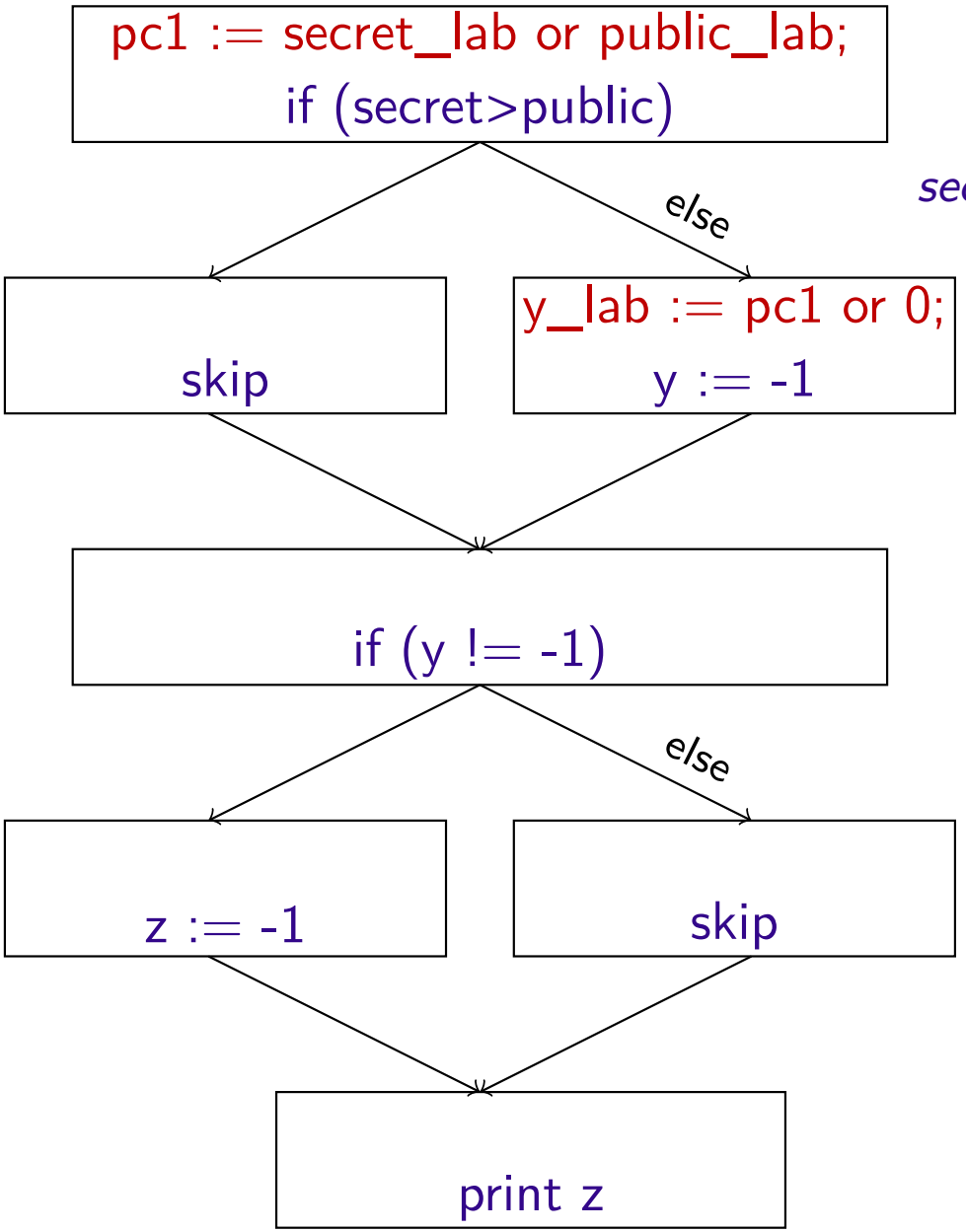
Information Flow Control for C?



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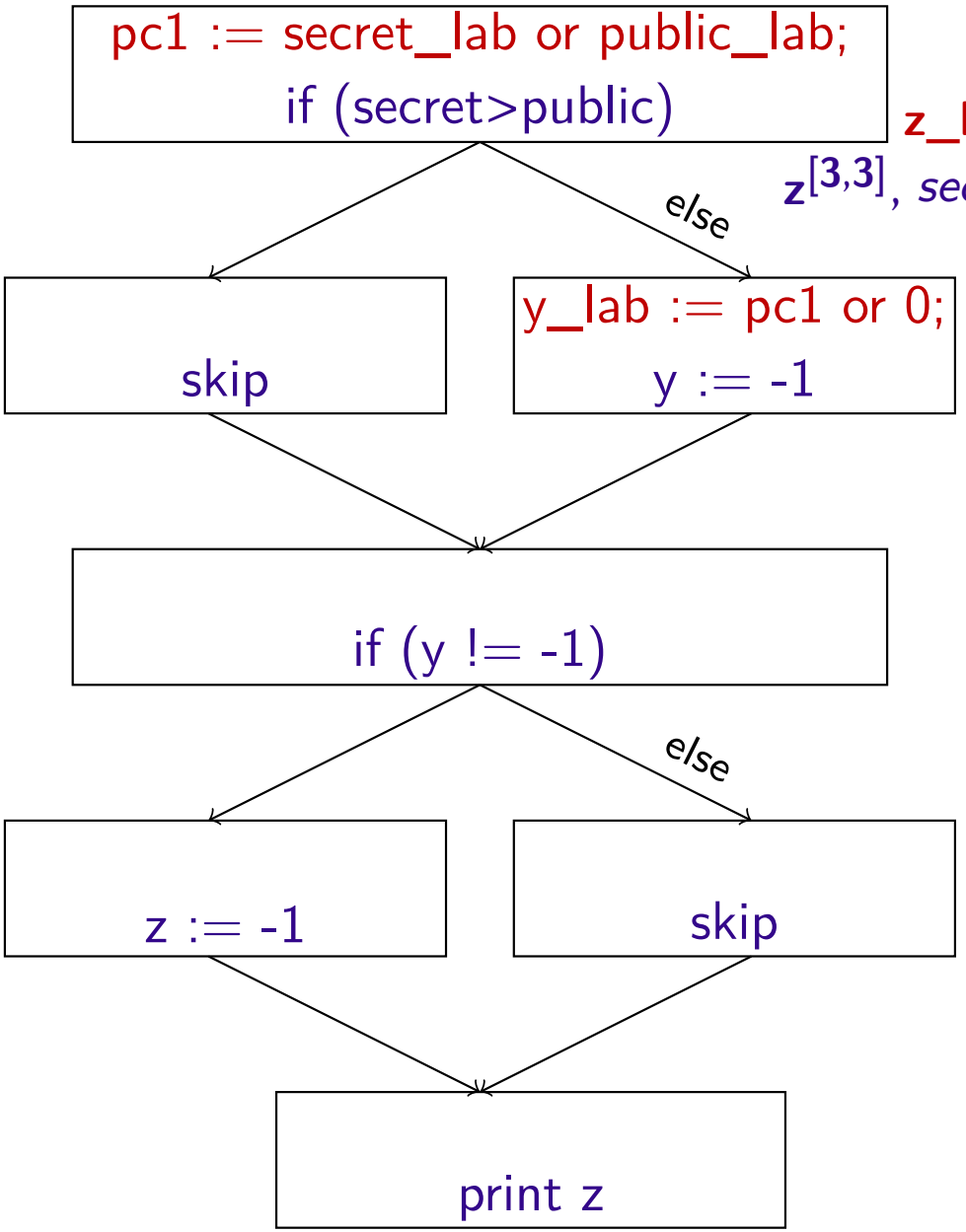

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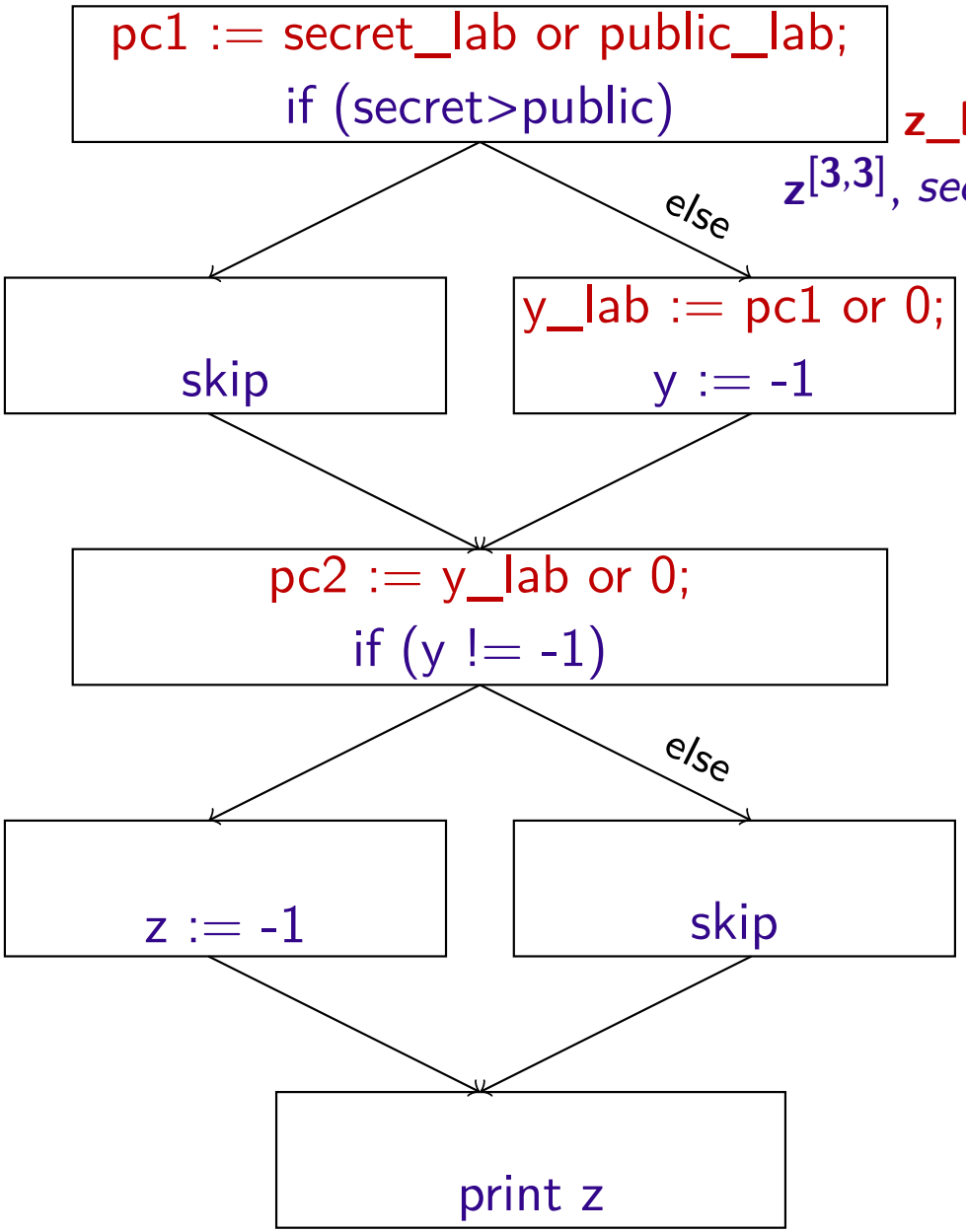

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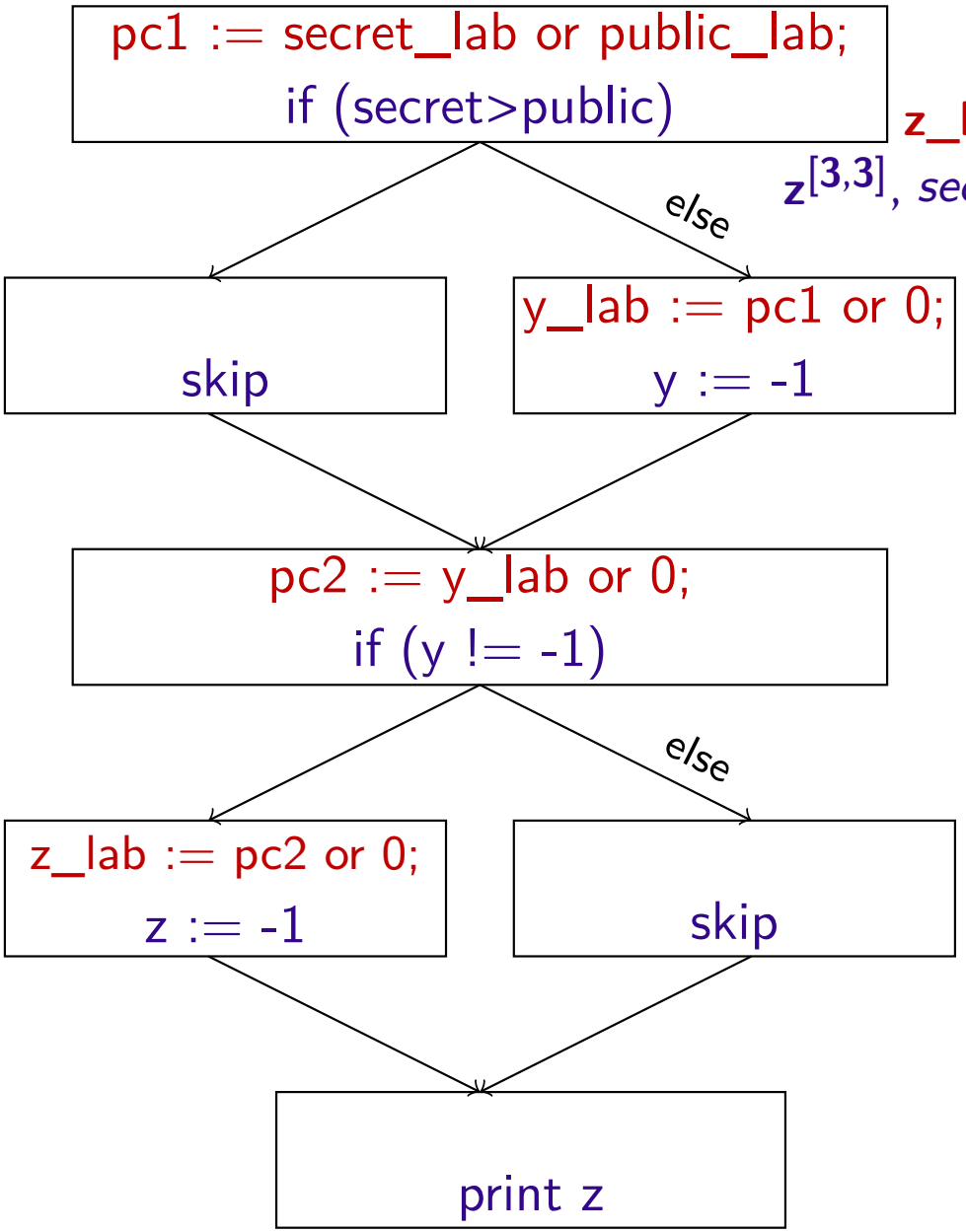

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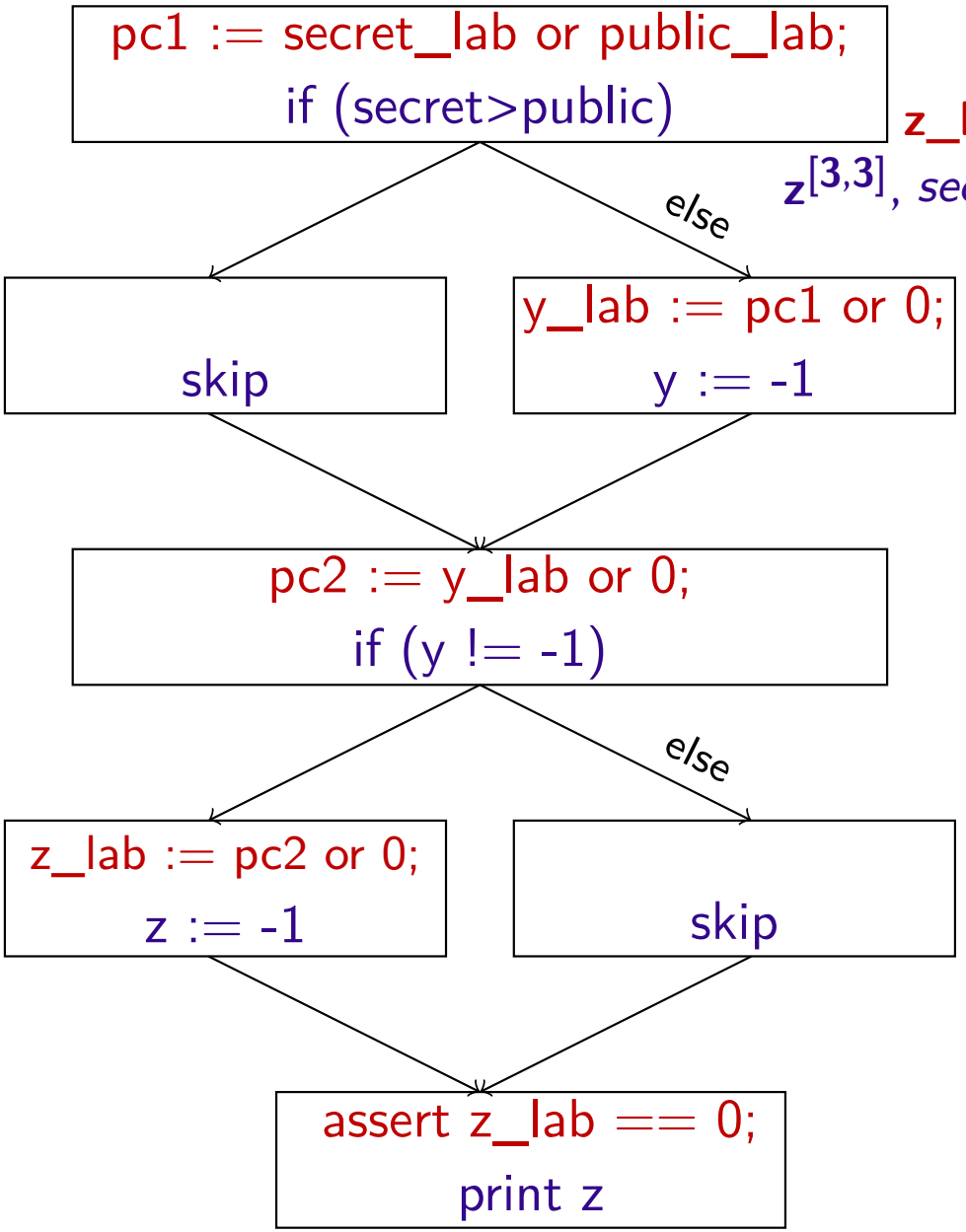

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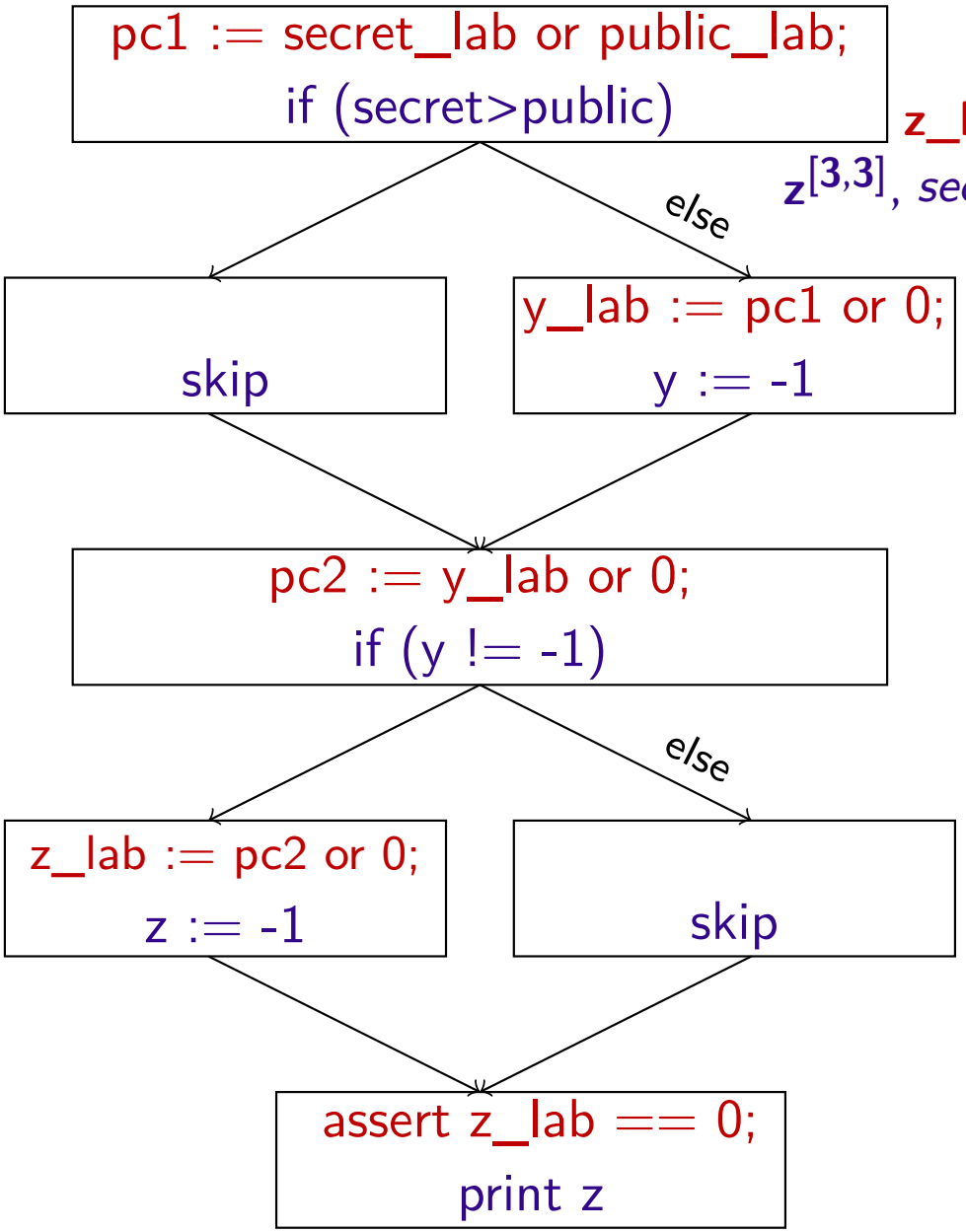

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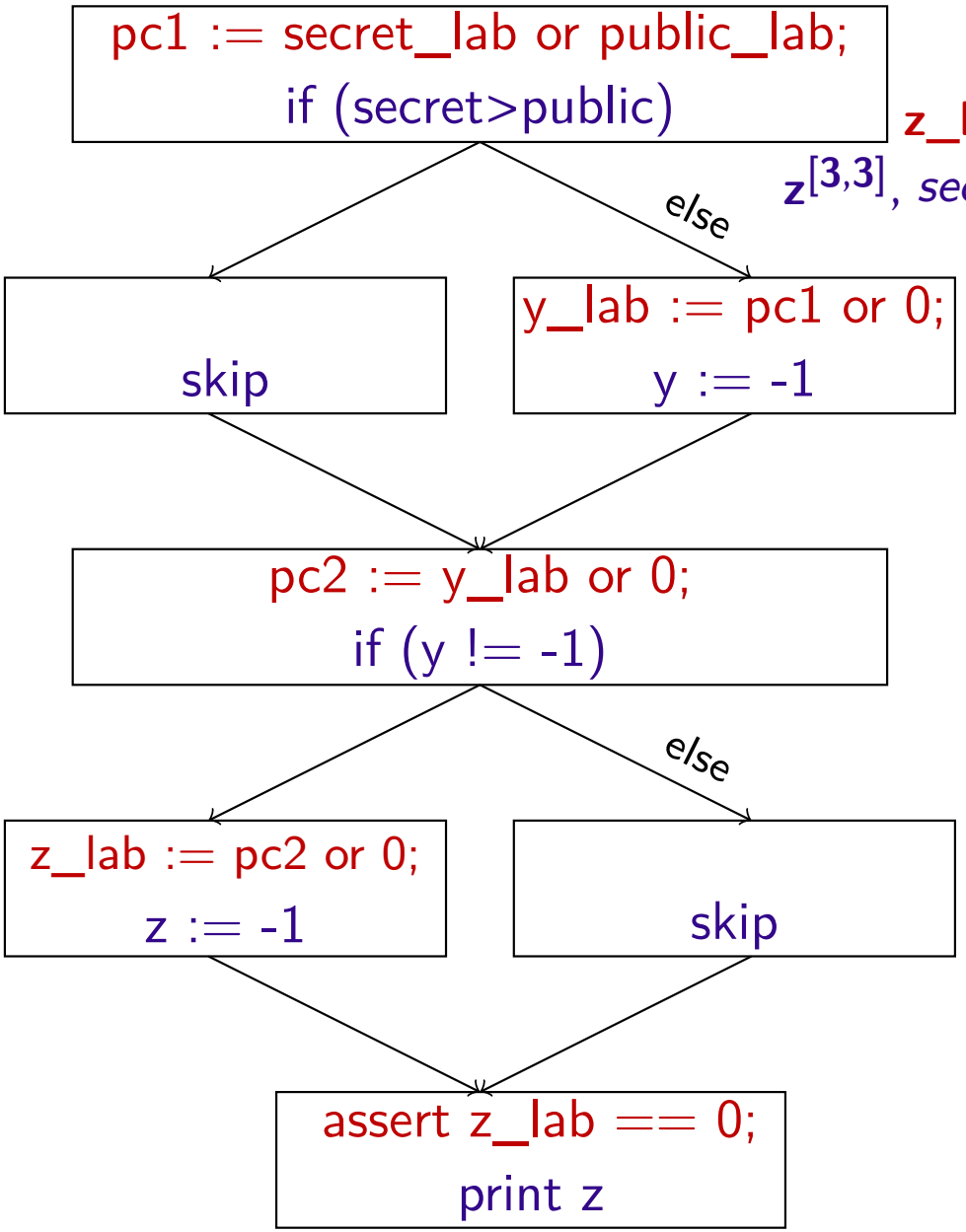
Information Flow Control for C?

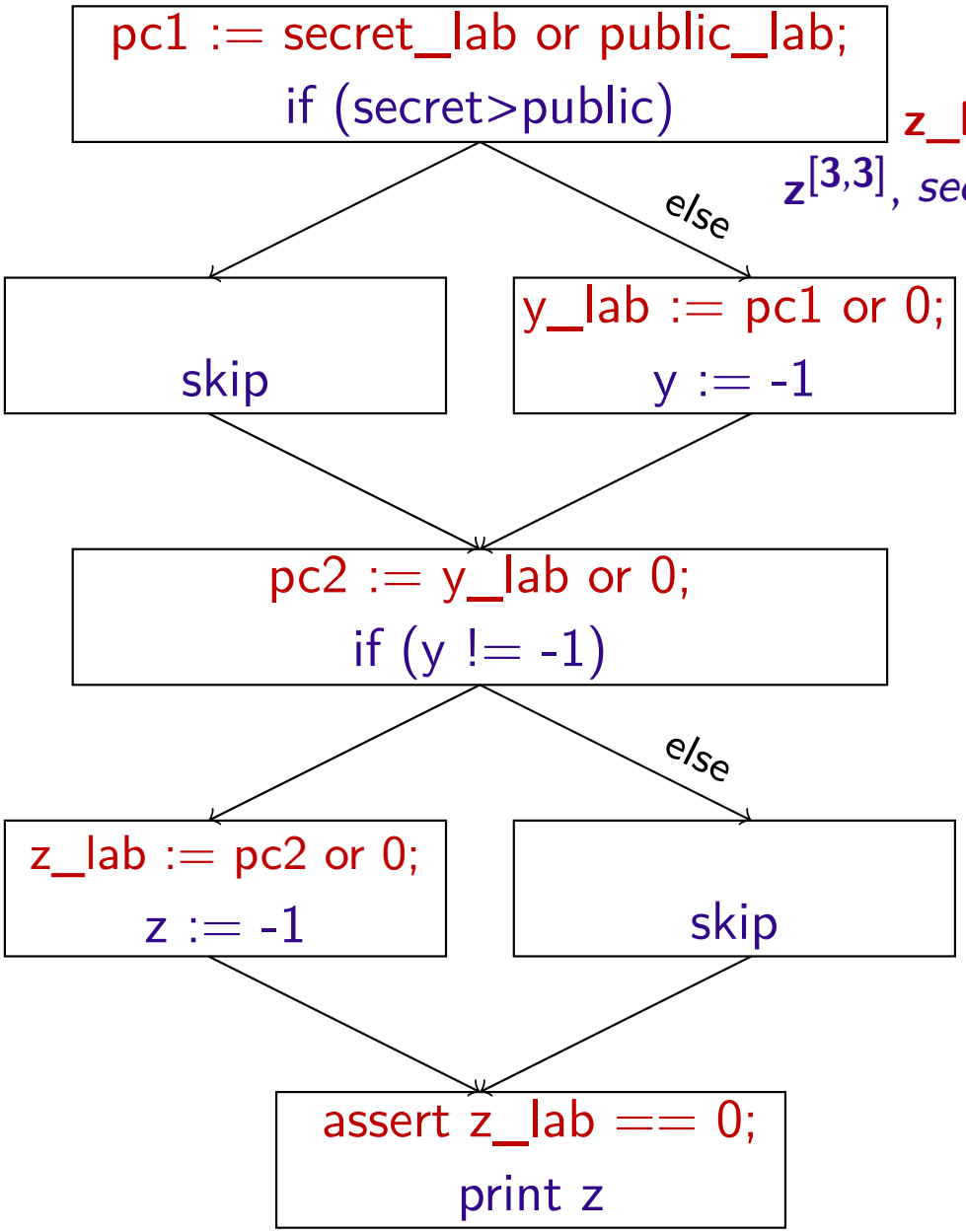


$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
$\mathbf{z\_lab^{[0,0]}}, y\_lab^{[0,0]}, pc1^{[1,1]}$
$\mathbf{z^{[3,3]}}, secret^{[minI,maxI]}, public^{[minI,maxI]}, y^{[3,3]}$

$y\_lab^{[0,0]}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$

$\mathbf{pc2^{[0,0]}}$	$\mathbf{pc2^{[1,1]}}$
$y\_lab^{[0,0]}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$
then	else

Information Flow Control for C?



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
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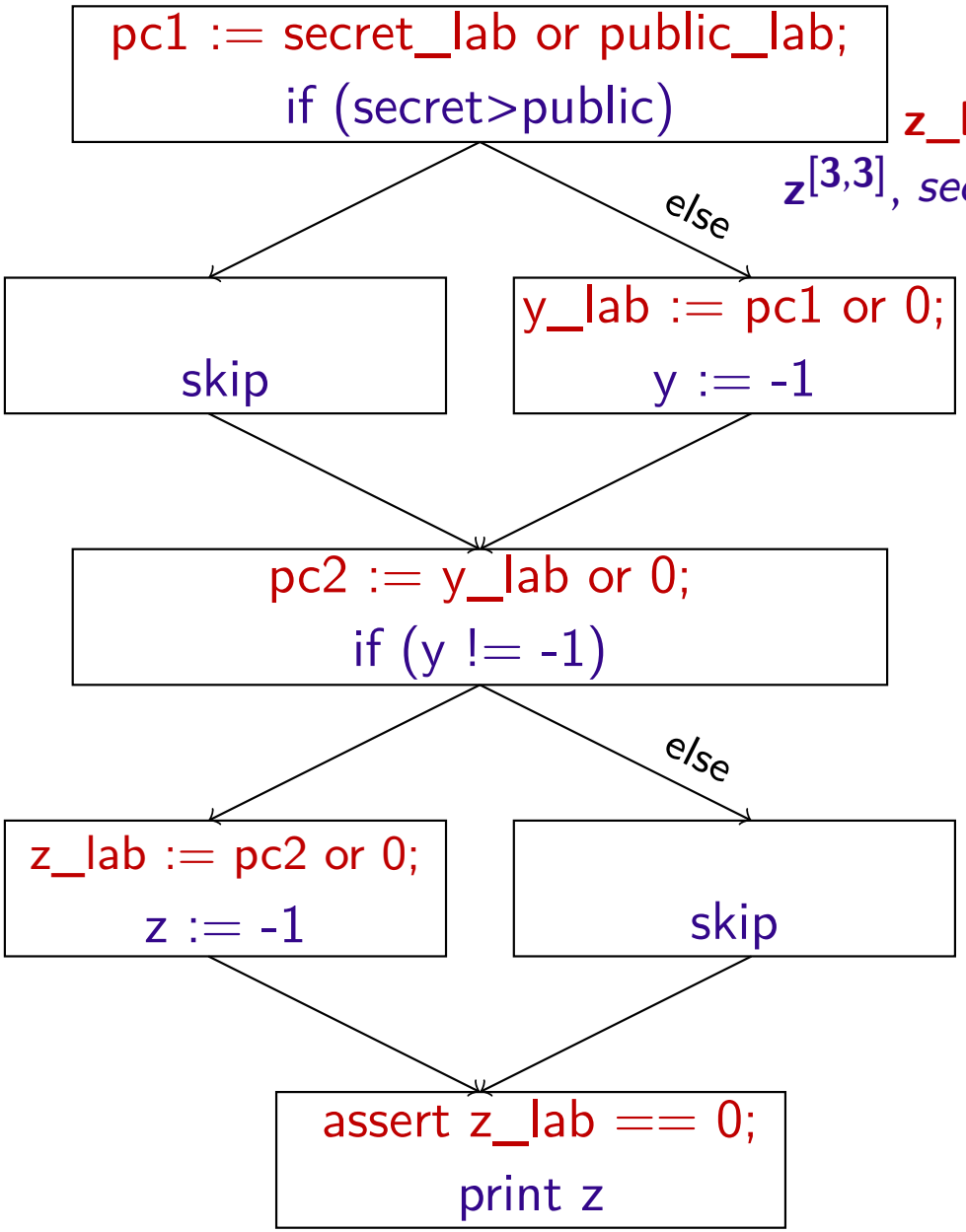
$y\_lab^{[0,0]}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$

$\mathbf{pc2^{[0,0]}}$	$\mathbf{pc2^{[1,1]}}$
$y\_lab^{[0,0]}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$

then / else

$pc2^{[0,0]}$	$pc2^{[1,1]}$
$\mathbf{z\_lab^{[0,0]}}$	$\mathbf{z\_lab^{[0,0]}}$
$\mathbf{z^{[-1,-1]}}$	$\mathbf{z^{[3,3]}}$



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
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$\mathbf{pc2^{[0,0]}}$	$\mathbf{pc2^{[1,1]}}$
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$y^{[3,3]}$	$y^{[-1,-1]}$
then	else
$pc2^{[0,0]}$	$pc2^{[1,1]}$
$\mathbf{z\_lab^{[0,0]}}$	$\mathbf{z\_lab^{[0,0]}}$
$\mathbf{z^{[-1,-1]}}$	$\mathbf{z^{[3,3]}}$

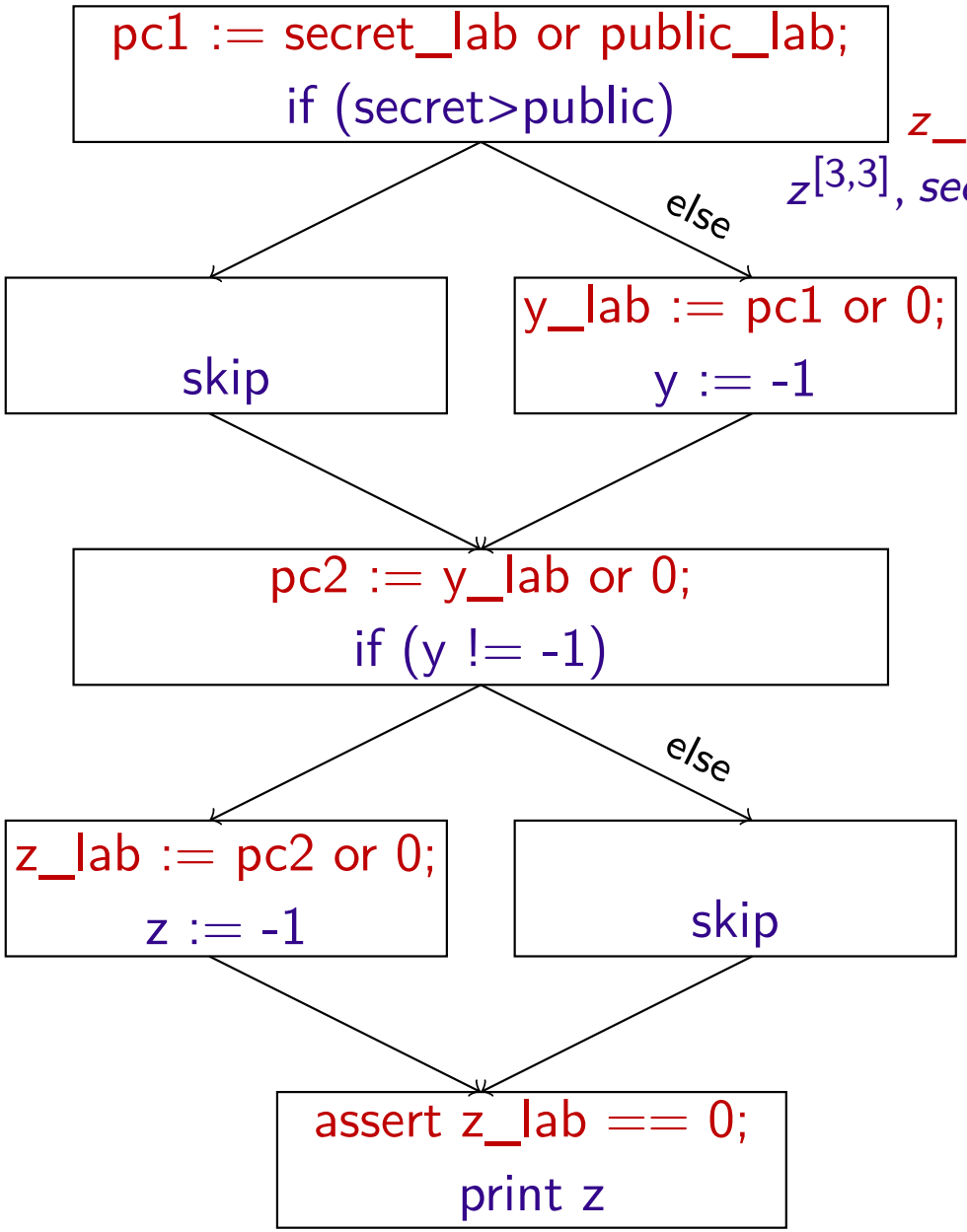
Information leak not detected

Non-interference is not a safety property [McLean,94] [Schneider,00]

Intuitively, even the fact that a variable is not modified during an execution may also leak sensitive information

Information Flow Monitoring [Le Guernic et al.,06] [Russo & Sabelfeld,10]

A prior static analysis of target programs computing the set of modified variables in non-executed conditional branches



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
$z\_lab^{[0,0]}, y\_lab^{[0,0]}, pc1^{[1,1]}$
$z^{[3,3]}, secret^{[minI,maxI]}, public^{[minI,maxI]}, y^{[3,3]}$

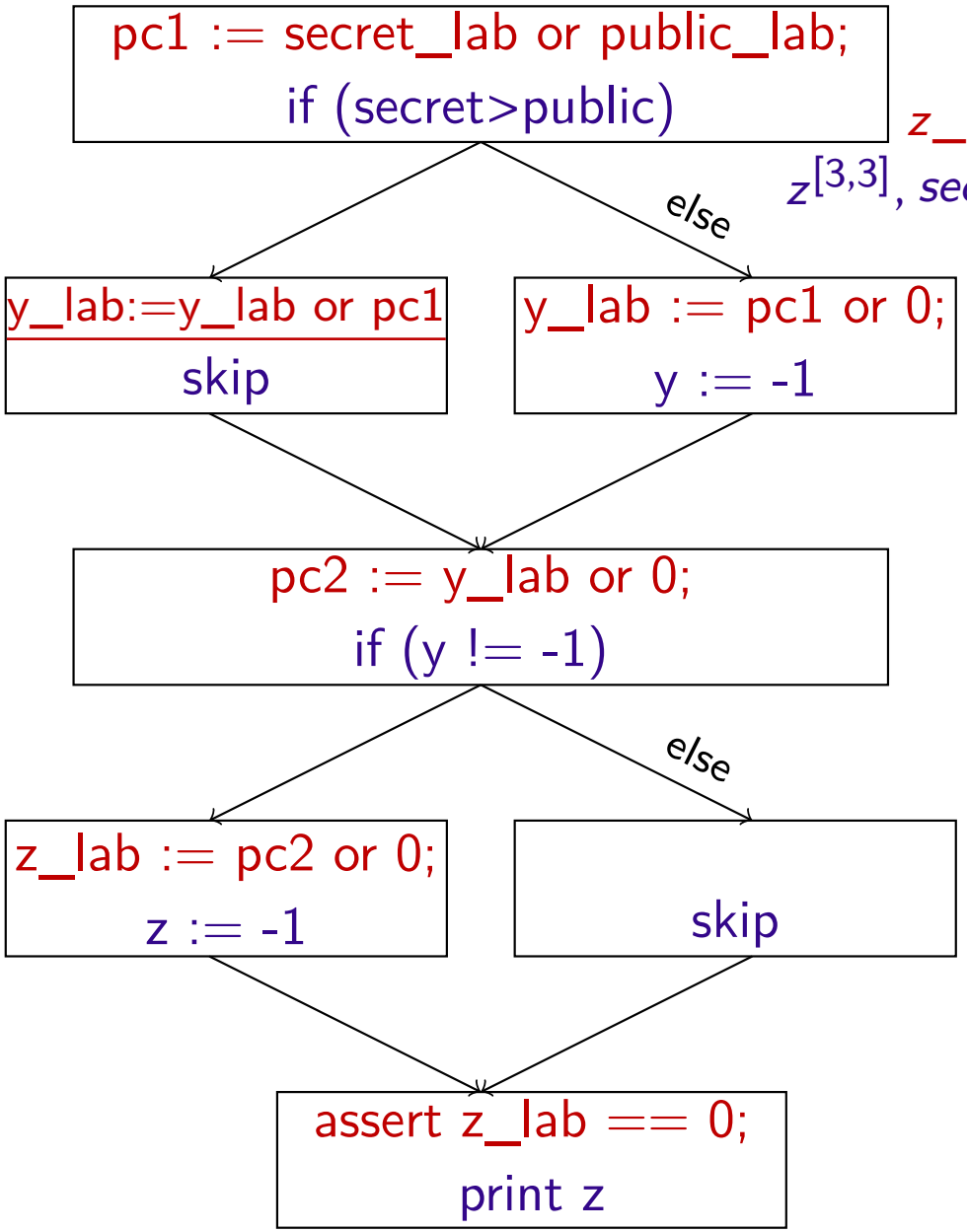
$y^{[3,3]}$	$y\_lab^{[1,1]}$ $y^{[-1,-1]}$

$y^{[3,3]}$	$pc2^{[1,1]}$ $y\_lab^{[1,1]}$ $y^{[-1,-1]}$

then | else

$\mathbf{z^{[-1,-1]}}$	$pc2^{[1,1]}$ $\mathbf{z^{[3,3]}}$

IF monitoring to the Rescue!



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$

$z\_lab^{[0,0]}, y\_lab^{[0,0]}, pc1^{[1,1]}$

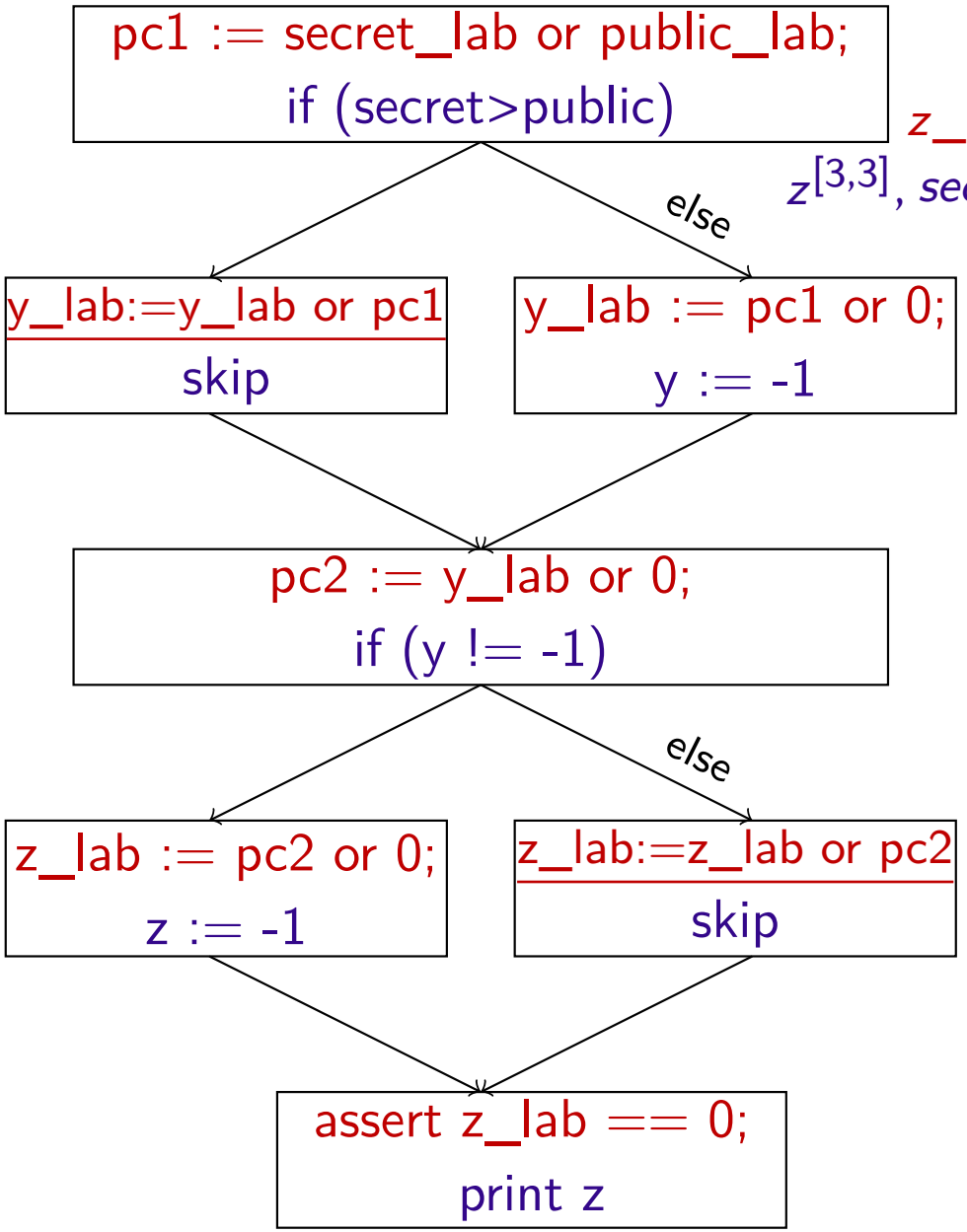
$z^{[3,3]}, secret^{[minI,maxI]}, public^{[minI,maxI]}, y^{[3,3]}$

$y^{[3,3]}$	$y\_lab^{[1,1]}$ $y^{[-1,-1]}$

$y^{[3,3]}$	$pc2^{[1,1]}$ $y\_lab^{[1,1]}$ $y^{[-1,-1]}$

then / else

$\mathbf{z^{[-1,-1]}}$	$pc2^{[1,1]}$ $\mathbf{z^{[3,3]}}$



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
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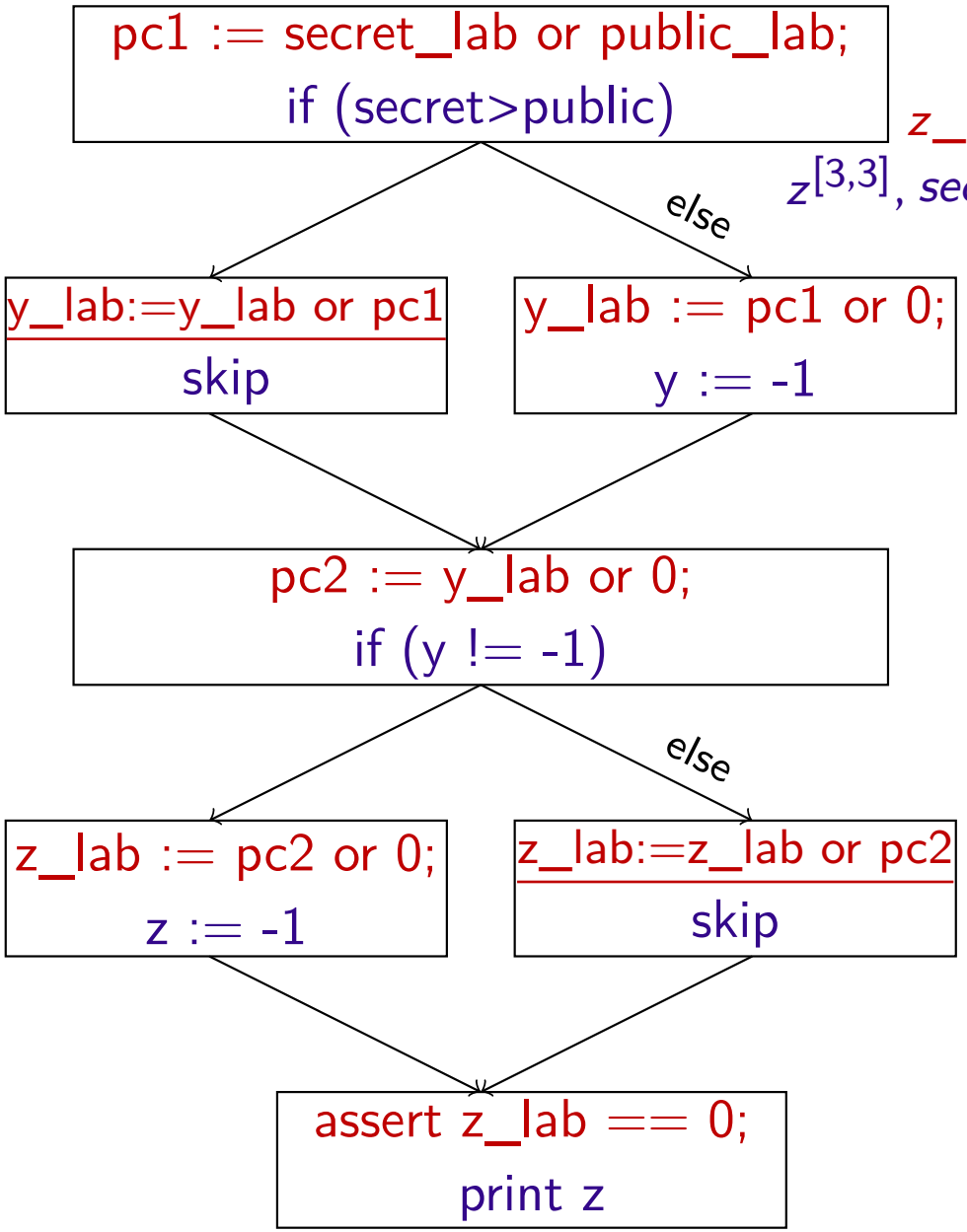
$y^{[3,3]}$	$y\_lab^{[1,1]}$
	$y^{[-1,-1]}$

$y^{[3,3]}$	$pc2^{[1,1]}$
	$y\_lab^{[1,1]}$
	$y^{[-1,-1]}$

then | else

$\mathbf{z^{[-1,-1]}}$	$pc2^{[1,1]}$
	$\mathbf{z^{[3,3]}}$



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$z\_lab^{[0,0]}, y\_lab^{[0,0]}, pc1^{[1,1]}$
$z^{[3,3]}, secret^{[minI,maxI]}, public^{[minI,maxI]}, y^{[3,3]}$

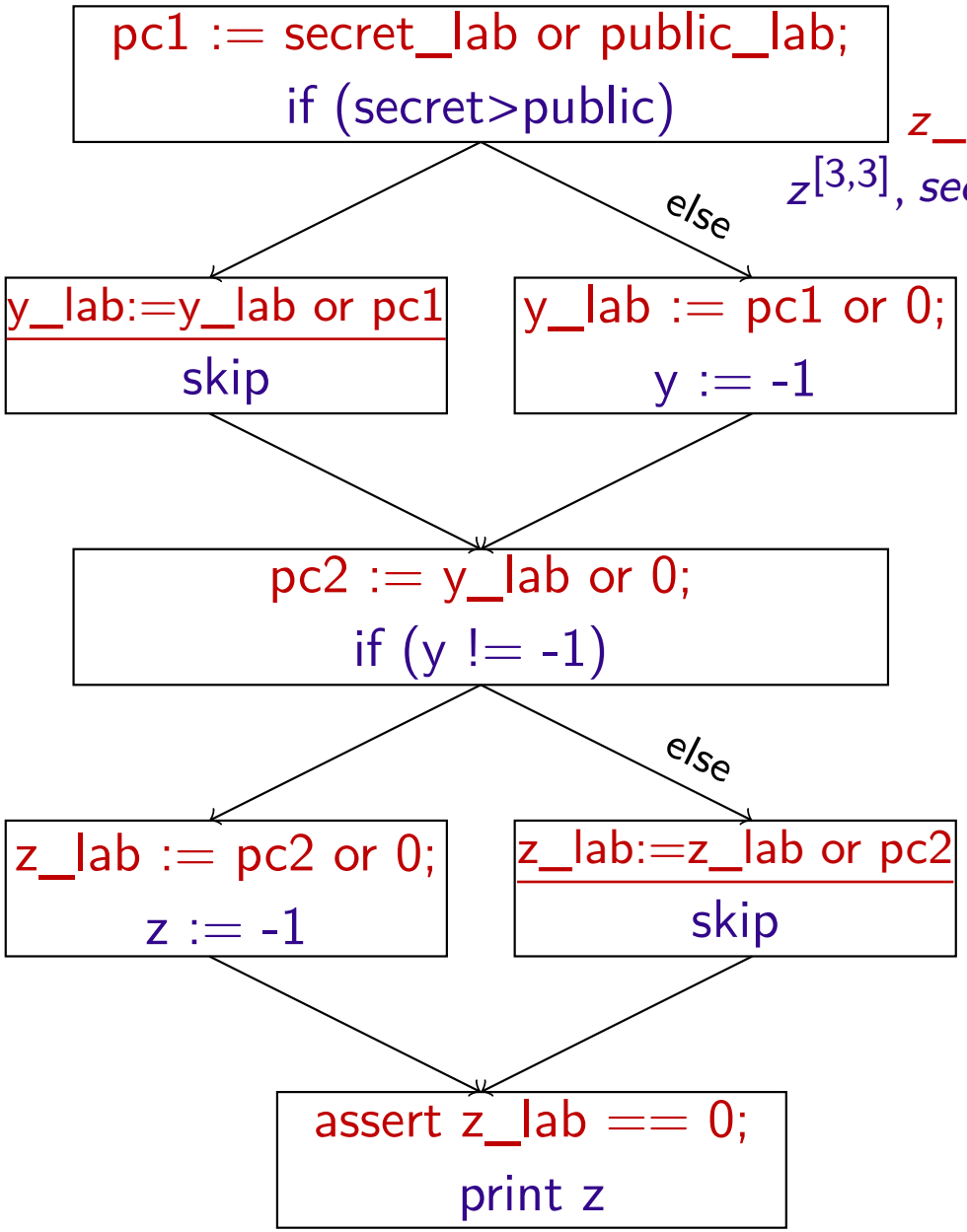
$\mathbf{y\_lab^{[1,1]}}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$

$y\_lab^{[1,1]}$	$pc2^{[1,1]}$
$y^{[3,3]}$	$y\_lab^{[1,1]}$
	$y^{[-1,-1]}$

then else

	$pc2^{[1,1]}$
$\mathbf{z^{[-1,-1]}}$	$\mathbf{z^{[3,3]}}$

IF monitoring to the Rescue!



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
$z\_lab^{[0,0]}, y\_lab^{[0,0]}, pc1^{[1,1]}$
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$\mathbf{y\_lab^{[1,1]}}$	$y\_lab^{[1,1]}$
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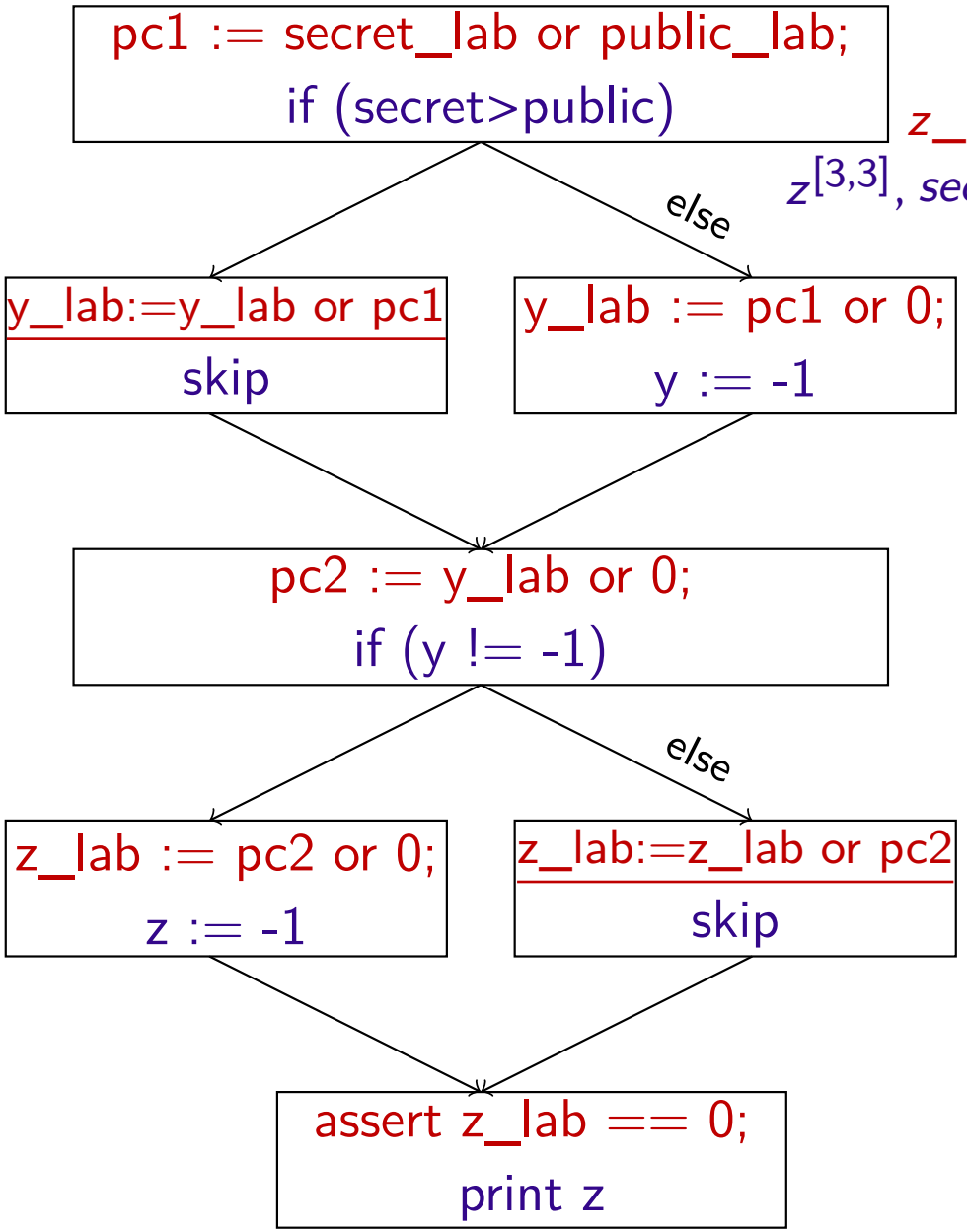
$\mathbf{pc2^{[1,1]}}$	$pc2^{[1,1]}$
$y\_lab^{[1,1]}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$
then	else
$pc2^{[1,1]}$	$pc2^{[1,1]}$
$\mathbf{z^{[-1,-1]}}$	$\mathbf{z^{[3,3]}}$



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
$z\_lab^{[0,0]}, y\_lab^{[0,0]}, pc1^{[1,1]}$
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$\mathbf{y\_lab^{[1,1]}}$	$y\_lab^{[1,1]}$
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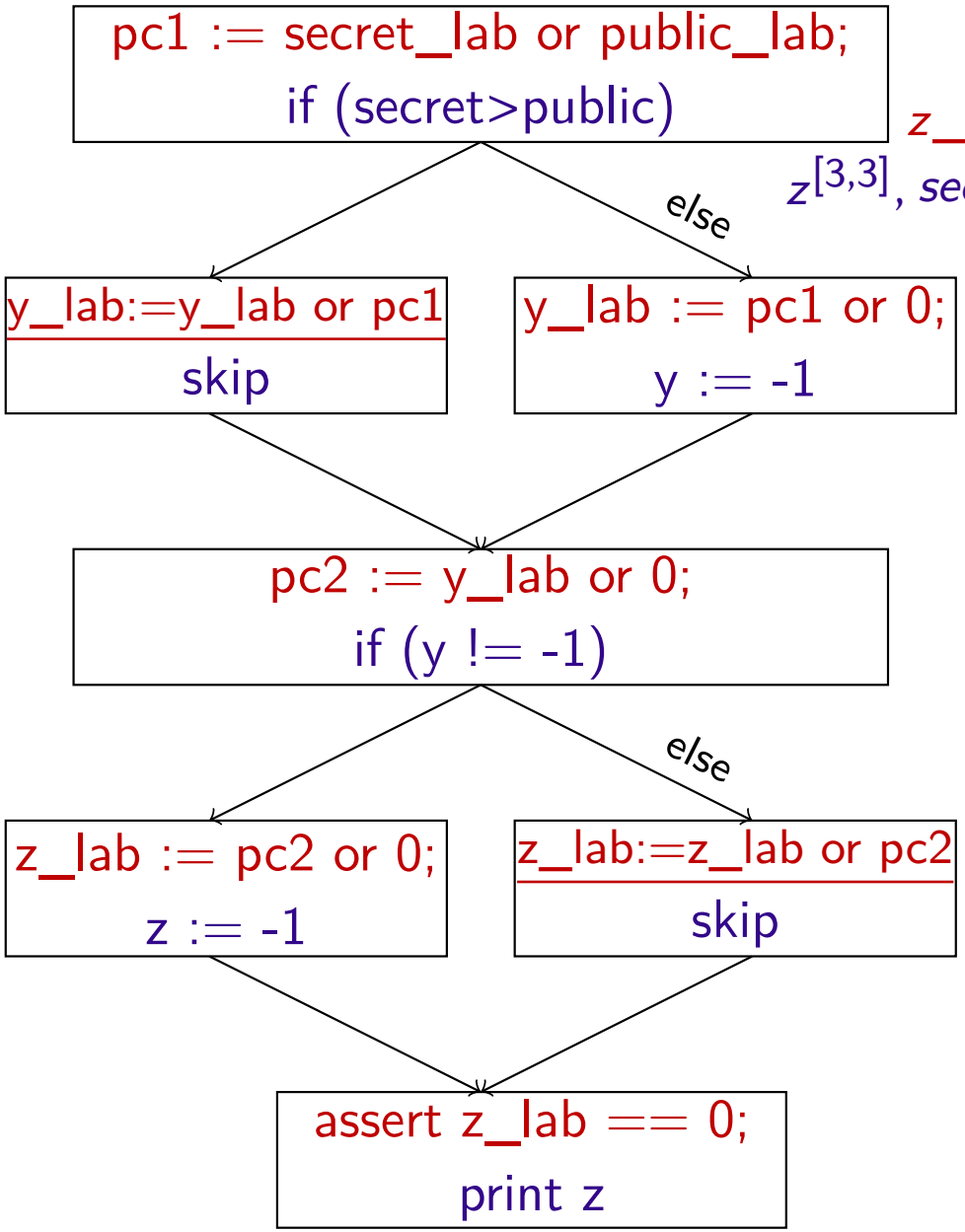
$\mathbf{pc2^{[1,1]}}$	$pc2^{[1,1]}$
$y\_lab^{[1,1]}$	$y\_lab^{[1,1]}$
$y^{[3,3]}$	$y^{[-1,-1]}$
then	else
$pc2^{[1,1]}$	$pc2^{[1,1]}$
$\mathbf{z\_lab^{[1,1]}}$	$\mathbf{z\_lab^{[1,1]}}$
$\mathbf{z^{[-1,-1]}}$	$\mathbf{z^{[3,3]}}$

IF monitoring to the Rescue!



$secret\_lab^{[1,1]}, public\_lab^{[0,0]}$
$z\_lab^{[0,0]}, y\_lab^{[0,0]}, pc1^{[1,1]}$
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$\mathbf{y\_lab^{[1,1]}}$	$y\_lab^{[1,1]}$
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$y^{[3,3]}$	$y^{[-1,-1]}$
then	else
$pc2^{[1,1]}$	$pc2^{[1,1]}$
$\mathbf{z\_lab^{[1,1]}}$	$\mathbf{z\_lab^{[1,1]}}$
$\mathbf{z^{[-1,-1]}}$	$\mathbf{z^{[3,3]}}$
⚠LEAK	⚠LEAK

```
1   int auth
2
3   int *leak
4
5
6   leak := &auth
7
8
9
10  print *leak
```

- Aliasing invariant: two expressions are aliased iff their auxiliary variables are aliased

```
1   int auth
2   label auth_lab
3   int *leak
4
5
6   leak := &auth
7
8
9
10  print *leak
```

- Aliasing invariant: two expressions are aliased iff their auxiliary variables are aliased

```
1   int auth
2   label auth_lab
3   int *leak
4   label leak_lab
5   label *leak_lab_d1
6   leak := &auth
7
8
9
10  print *leak
```

- Aliasing invariant: two expressions are aliased iff their auxiliary variables are aliased

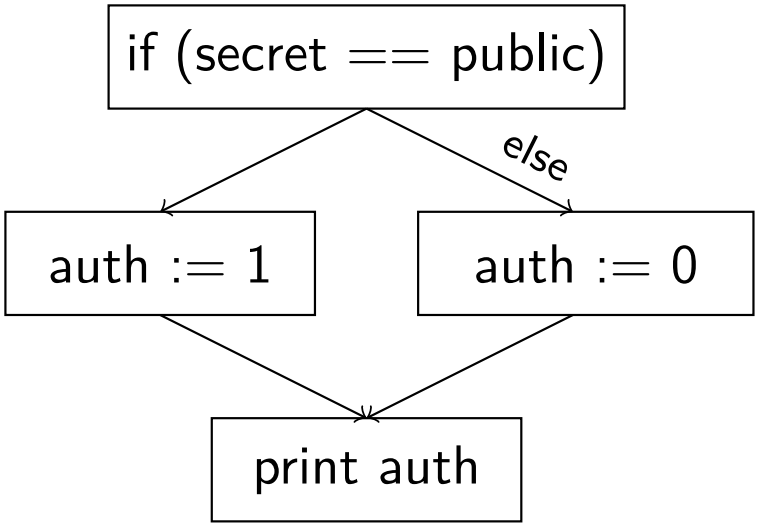
```
1   int auth
2   label auth_lab
3   int *leak
4   label leak_lab
5   label *leak_lab_d1
6   leak := &auth
7   leak_lab := 0
8   leak_lab_d1 := &auth_lab
9
10  print *leak
```

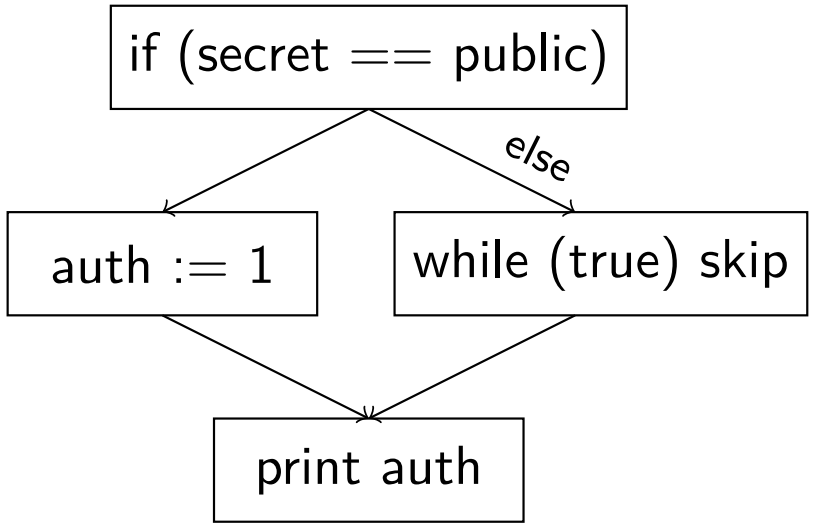
- Aliasing invariant: two expressions are aliased iff their auxiliary variables are aliased

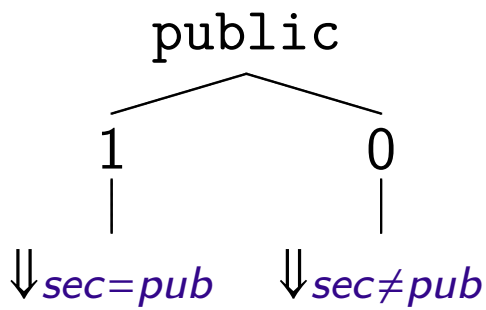
```
1   int auth
2   label auth_lab
3   int *leak
4   label leak_lab
5   label *leak_lab_d1
6   leak := &auth
7   leak_lab := 0
8   leak_lab_d1 := &auth_lab
9   assert leak_lab or *leak_lab_d1 == 0
10  print *leak
```

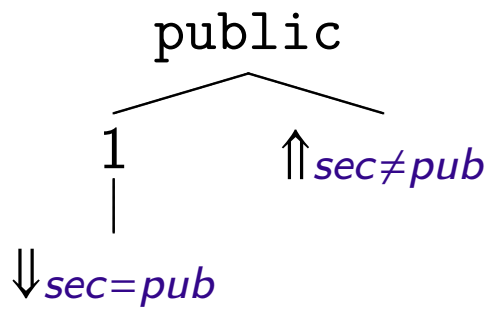
- Aliasing invariant: two expressions are aliased iff their auxiliary variables are aliased

- Our approach:
  - Sound hybrid information flow monitor for a language supporting pointers and aliasing
  - Sound inlining approach for our monitor [Assaf et al.,13a & 13b]
  - Implemented the inlining approach as a Frama-C plug-in: support of arrays, pointer arithmetics, functions, structures...
- Verifying TINI through:
  - Static analysis by relying on off-the-shelf tools, or
  - Monitoring
- Future work: a prior static analysis guiding the inlining approach to support casts, unions and dynamic allocation...

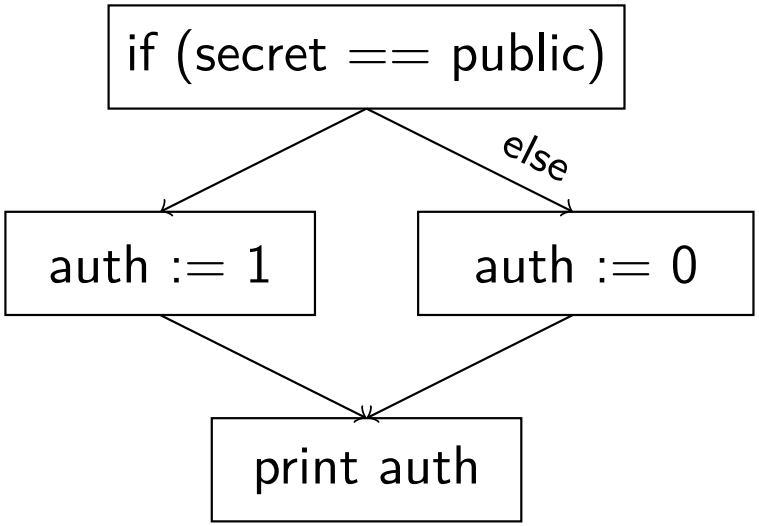


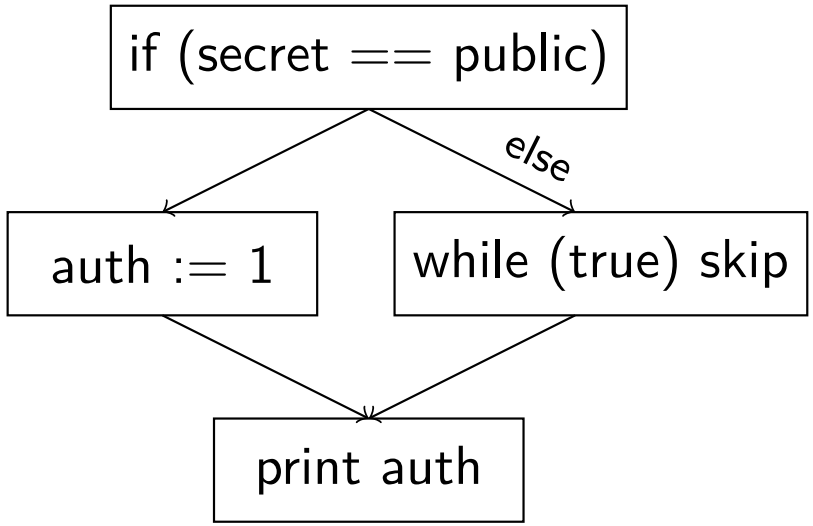




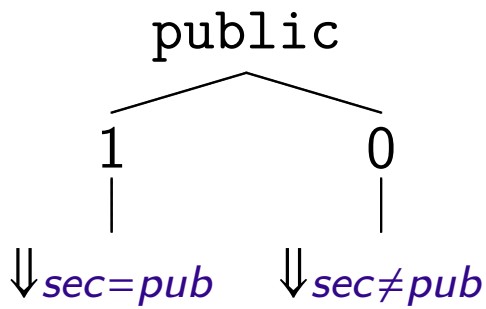


- From attackers' perspective: both programs are equivalent

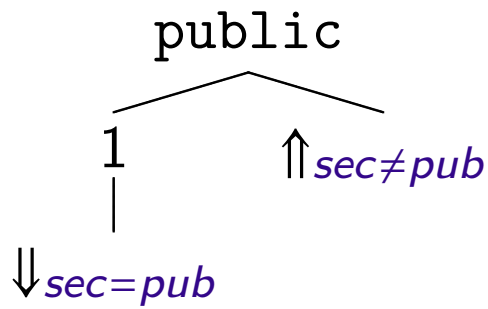




⚠Interferent program



Non-interferent program



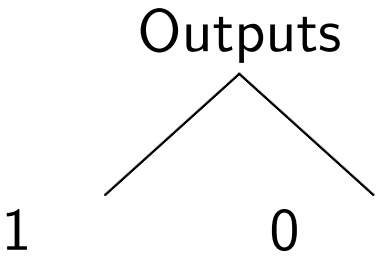
- From attackers' perspective: both programs are equivalent

- Information leaks due to the observation of divergence are discarded
  - The probability of polynomial time attackers guessing the secret is negligible in the size of the secret [Askarov et al.,08]
  - Let us prove security of programs wrt. this exact assumption
  - A flavour of Relative Secrecy [Volpano and Smith,00]

The framework of min-entropy/min-capacity [Smith, 09 & 11]

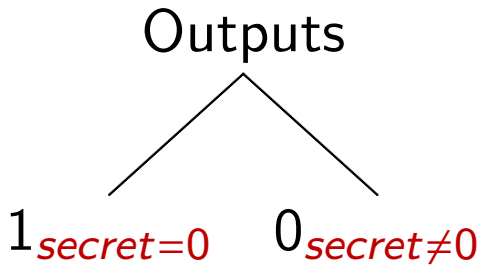
Quantifying the leakage wrt. the probability of attackers guessing the secret

```
1 if (secret == 0) {
2     print 1 }
3 else {
4     print 0 }
```



- What's the probability of attackers guessing the secret after observing an output? ($secret \in [0, 2^N - 1]$)

```
1 if (secret == 0) {
2     print 1 }
3 else {
4     print 0 }
```



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1 if (secret == 0) {
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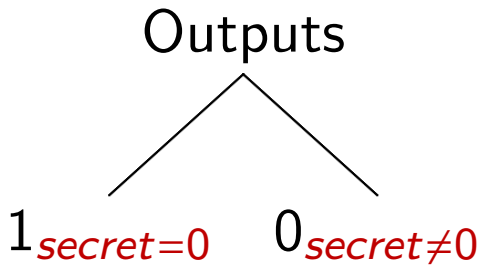

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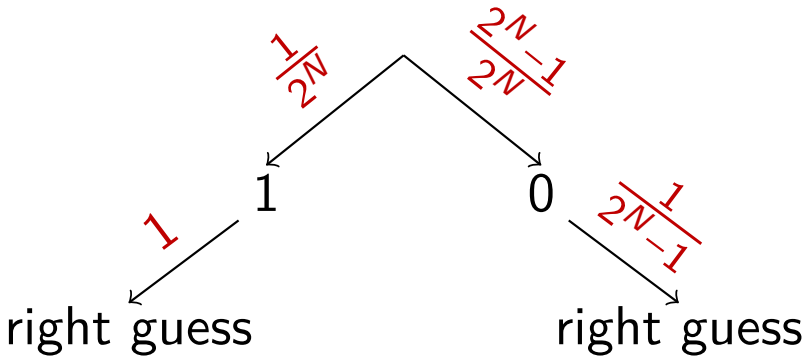

```
1 if (secret == 0) {
2     print 1 }
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```
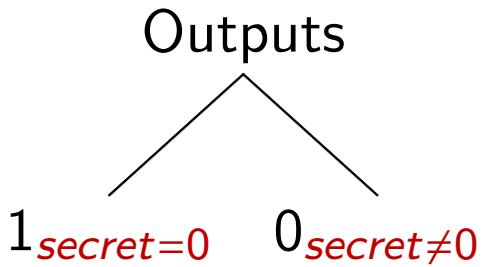
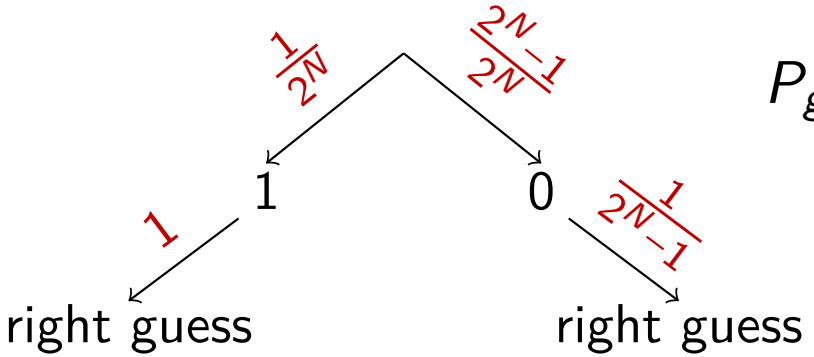
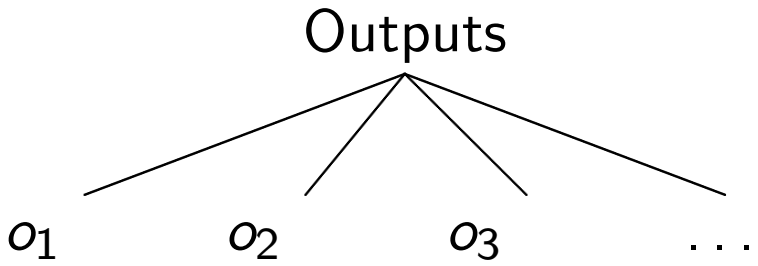



- What's the probability of attackers guessing the secret after observing an output? ($secret \in [0, 2^N - 1]$)

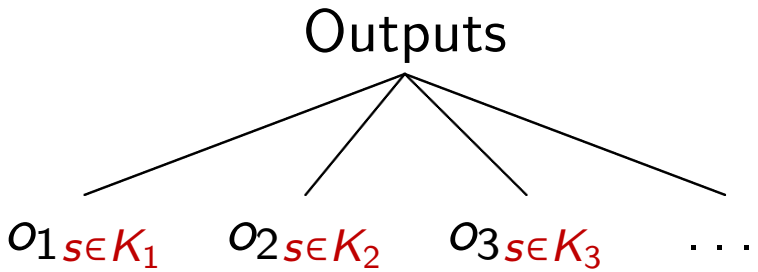


$$P_{guess} = \frac{\cancel{1}}{2^N} \times \frac{1}{\cancel{1}} + \frac{\cancel{2^N - 1}}{2^N} \times \frac{1}{\cancel{2^N - 1}}$$
$$= \frac{2}{2^N}$$

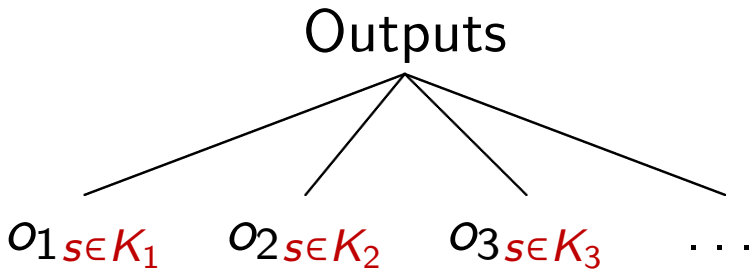
- A pattern :



- A pattern :

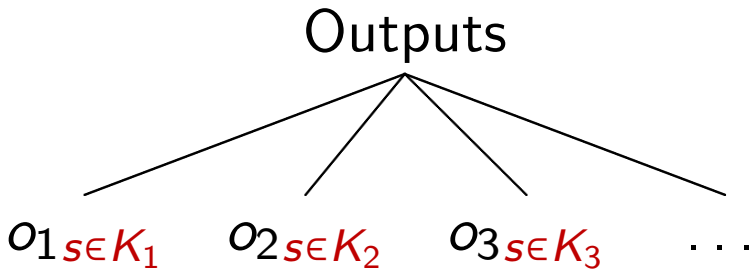


- A pattern :



$$P_{guess} = \sum_{o_i \in Outputs} \frac{\cancel{|K_i|}}{2^N} \times \frac{1}{\cancel{|K_i|}}$$
$$= \frac{|Outputs|}{2^N}$$

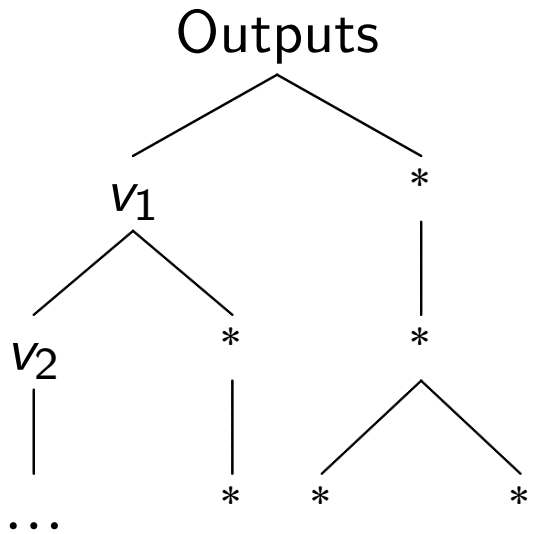
- A pattern :

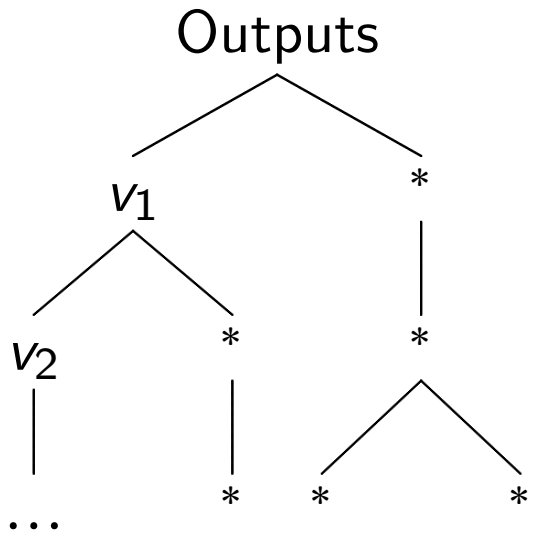


$$P_{guess} = \sum_{o_i \in Outputs} \frac{\cancel{|K_i|}}{2^N} \times \frac{1}{\cancel{|K_i|}} = \frac{|Outputs|}{2^N}$$

- The leakage of a program in bits, assuming a uniform distribution $\vec{\pi}_u$ of the secret: [Smith,09 & 11]

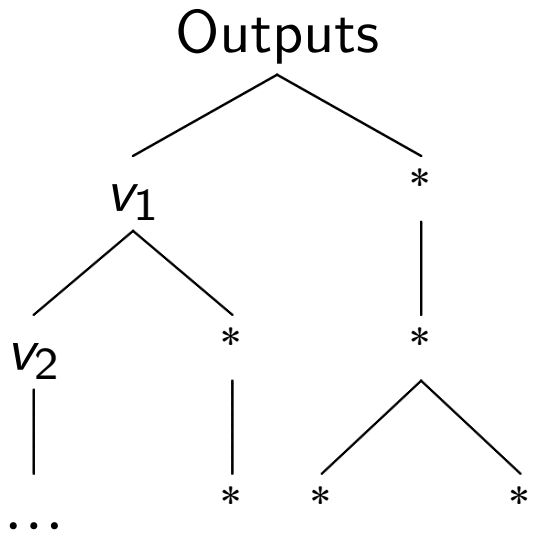
$$\begin{aligned} \mathscr{L}_{\vec{\pi}_u} &\triangleq \text{Initial uncertainty} - \text{Remaining uncertainty} \\ &= -\log_2 \frac{1}{2^N} \quad - \quad (-\log_2 \frac{|Outputs|}{2^N}) \\ &= \log_2 |Outputs| \end{aligned}$$


Outputs
v_1
*
v_2
*
*
...
*
*
*



- Polynomial time attackers observe only a polynomial amount of outputs:

$$o_i = v_1 \cdot v_2 \cdot v_3 \ldots \text{ such that } \text{length}(o_i) \leq b, \text{ with } log(b) = o(N)$$



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$$o_i = v_1 \cdot v_2 \cdot v_3 \ldots \text{ such that } \text{length}(o_i) \leq b, \text{ with } log(b) = o(N)$$

- Relative Secrecy for deterministic programs:

$$\log_2 |Outputs_b| = o(N) \text{ when } log(b) = o(N)$$

- A problem : how do we count the cardinal of outputs? ($\mathscr{ML} = \log_2 |Outputs_b|$)

```
1  x := s mod 4
2  print x
```


```
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```

- A problem : how do we count the cardinal of outputs? ($\mathscr{ML} = \log_2 |Outputs_b|$)

```
1  x := s mod 4
2  print x
```

1 $s \mapsto 0, s \mapsto 1, \ldots, s \mapsto 2^N - 1$

2 $x \mapsto 0, x \mapsto 1, x \mapsto 2, x \mapsto 3$

  - finding the set of final states,


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- A theory of sound semantics approximations : abstract interpretation

```
1  x := s mod 4
2  print x
```

1 $s^{[0,2^N-1]}$

2 $x^{[0,3]}$

$\mathscr{ML} = log_2(4)$

$= 2\ bits$

- Over-approximating the set of reachable final states : a fairly large body of the literature in abstract interpretation ...
  - quantifying information flow by a generic abstract interpretation (over-approximated bounds) and symbolic execution (under-approximated bounds)

    [Köpf and Rybalchenko, 2010 & 2013]

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```
1  x := s mod 2
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```

0 $s \mapsto [0, 2^N - 1], input \mapsto [0, 2^N - 1]$

1 $x \mapsto [0, 1]$

2 $x \mapsto [0, 2^N - 1]$

$\mathscr{ML} = \log_2 2^N = N$ *bits*? no!

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$\mathscr{ML} = \log_2 2^N = N$ *bits*? no!

- Second limitation : intermediate outputs?

- For each attacker-controlled low input, we have a channel – a sub-program – possibly leaking information

```
1 x := s mod 2
2 x :=   x + 1
3 print x
```

```
1 x := s mod 2
2 x :=   x + 3
3 print x
```

...

```
1 x := s mod 2
2 x :=   x + 2
3 print x
```

```
1 x := s mod 2
2 x :=   x + 4
3 print x
```

In fact, for each one of these sub-programs :

$$\mathscr{ML} = \log_2 |Outputs| = log_2 2 = 1 \ bit$$

- Compute the cardinal of reachable states – of outputs – for each possible public input?

	sub-program 0	sub-program 1	...	sub-program $2^N - 1$
pp_1	$s^{[0,2^N-1]}\underline{input^{[0,0]}}$	$s^{[0,2^N-1]}\underline{input^{[1,1]}}$		$s^{[0,2^N-1]}\underline{input^{[2^N-1,2^N-1]}}$
pp_2	$x^{[0,1]}s^{[0,2^N-1]}input^{[0,0]}$	$x^{[0,1]}s^{[0,2^N-1]}input^{[1,1]}$		$x^{[0,1]}s^{[0,2^N-1]}input^{[2^N-1,2^N-1]}$
pp_3	$x^{[0,1]}s^{[0,2^N-1]}input^{[0,0]}$	$x^{[1,2]}s^{[0,2^N-1]}input^{[1,1]}$		$x^{[2^N-1,2^N]}s^{[0,2^N-1]}input^{[2^N-1,2^N]}$
$\sharp$	2	2		2

- Compute the cardinal of reachable states – of outputs – for each possible public input? computationally inefficient!

	sub-program 0	sub-program 1	...	sub-program $2^N - 1$
pp_1	$s^{[0,2^N-1]}\underline{input^{[0,0]}}$	$s^{[0,2^N-1]}\underline{input^{[1,1]}}$		$s^{[0,2^N-1]}\underline{input^{[2^N-1,2^N-1]}}$
pp_2	$x^{[0,1]}s^{[0,2^N-1]}input^{[0,0]}$	$x^{[0,1]}s^{[0,2^N-1]}input^{[1,1]}$		$x^{[0,1]}s^{[0,2^N-1]}input^{[2^N-1,2^N-1]}$
pp_3	$x^{[0,1]}s^{[0,2^N-1]}input^{[0,0]}$	$x^{[1,2]}s^{[0,2^N-1]}input^{[1,1]}$		$x^{[2^N-1,2^N]}s^{[0,2^N-1]}input^{[2^N-1,2^N]}$
$\sharp$	2	2		2

- Let us abstract more... And keep only the cardinal of values

$$pp_1 : \quad s^{2^N} \quad input^1$$

- A dedicated abstract domain computing an over-approximation of the cardinal of values a variable can take when attackers provide public inputs

```
1 x := s mod 2
2 x :=   x * input
3 print x
```

- A first step to quantify information flow for programs with low inputs
- Towards the combination of multiple domains to refine the cardinal abstraction

- A dedicated abstract domain computing an over-approximation of the cardinal of values a variable can take when attackers provide public inputs

```
1  x := s mod 2
2  x :=   x * input
3  print x
```

0 $s \mapsto (\{pp_0\}, 2^N), input \mapsto (\{pp_0\}, 1)$

1 $x \mapsto (\{pp_1\}, 2)$

2 $x \mapsto (\{pp_2\}, 2)$

$\mathscr{ML} = \log_2(2) = 1\ bit$

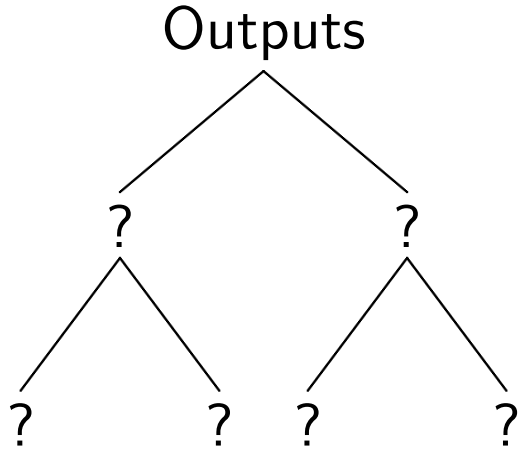
- A first step to quantify information flow for programs with low inputs
- Towards the combination of multiple domains to refine the cardinal abstraction

```
1  x := s mod 2
2  print x
3  x :=  s * input
4  print x
```

$1 \quad x \mapsto (\{pp_1\}, 2)$

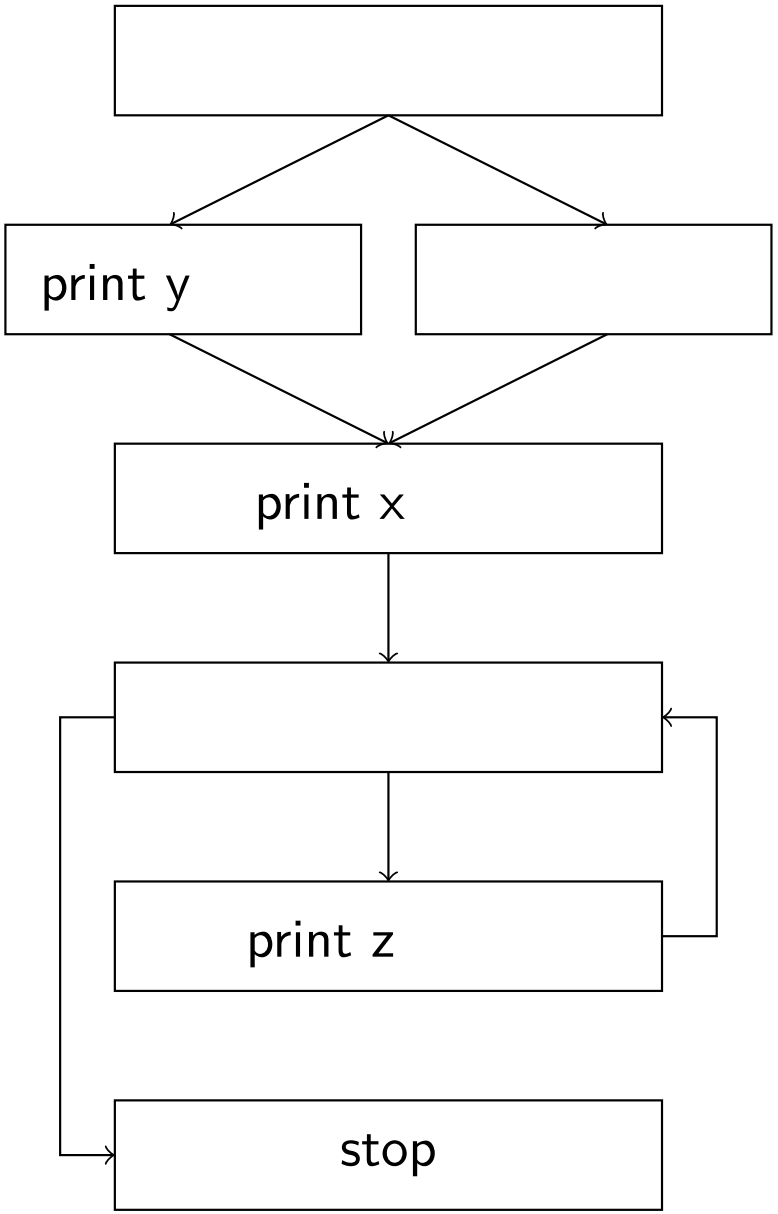
$3 \quad x \mapsto (\{pp_3\}, 2)$

- Computing a regular specification representing attackers' observations

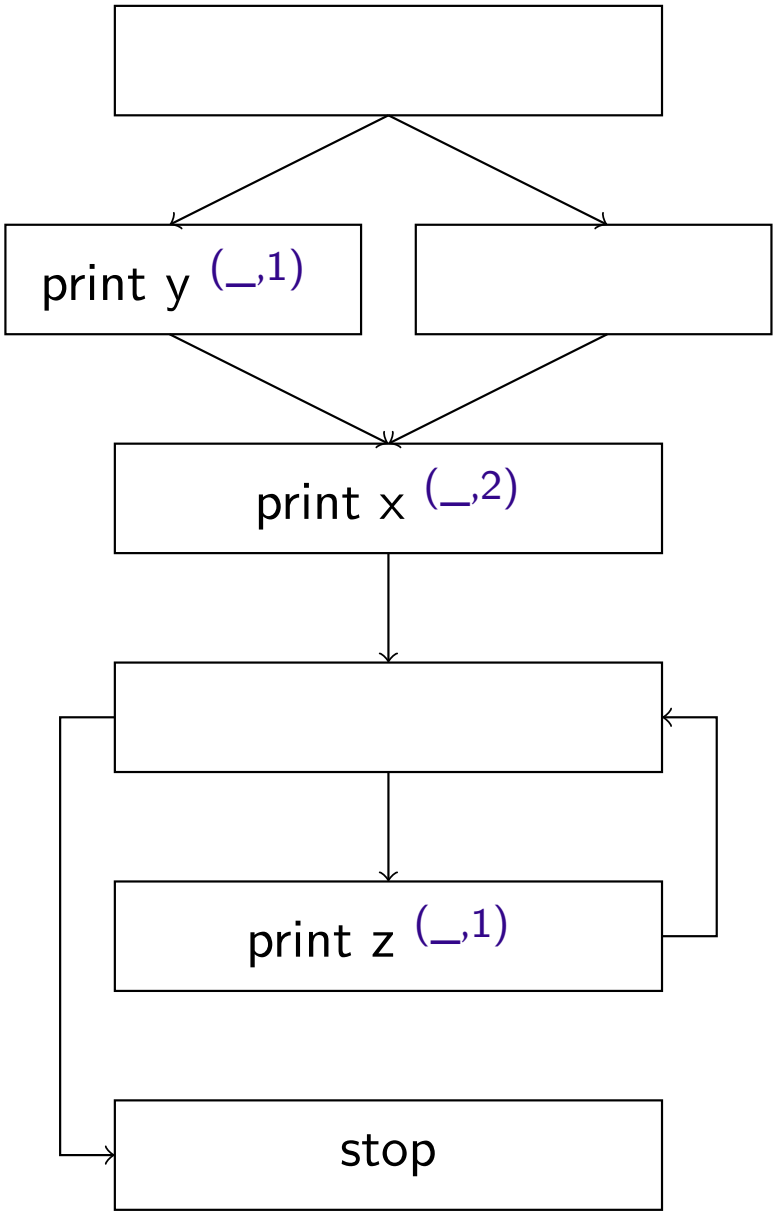


- $\mathscr{O}^2 \triangleq$ an atomic combinatorial class containing 2 undefined observations of size 1
- Attackers' observations :

$$\mathscr{C} = \mathscr{O}^2 \cdot \mathscr{O}^2$$



- Regular specifications:
  - concatenation $\cdot$
  - combinatorial sum $\oplus$
  - sequence construction *



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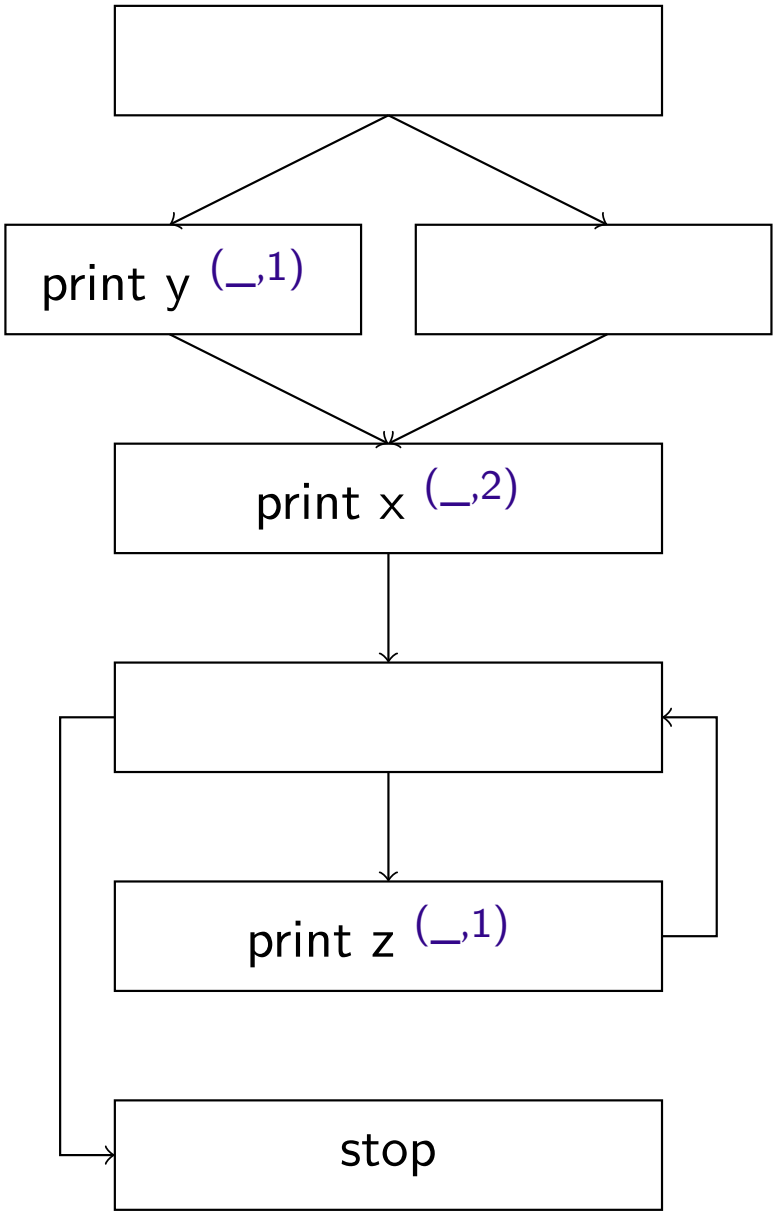

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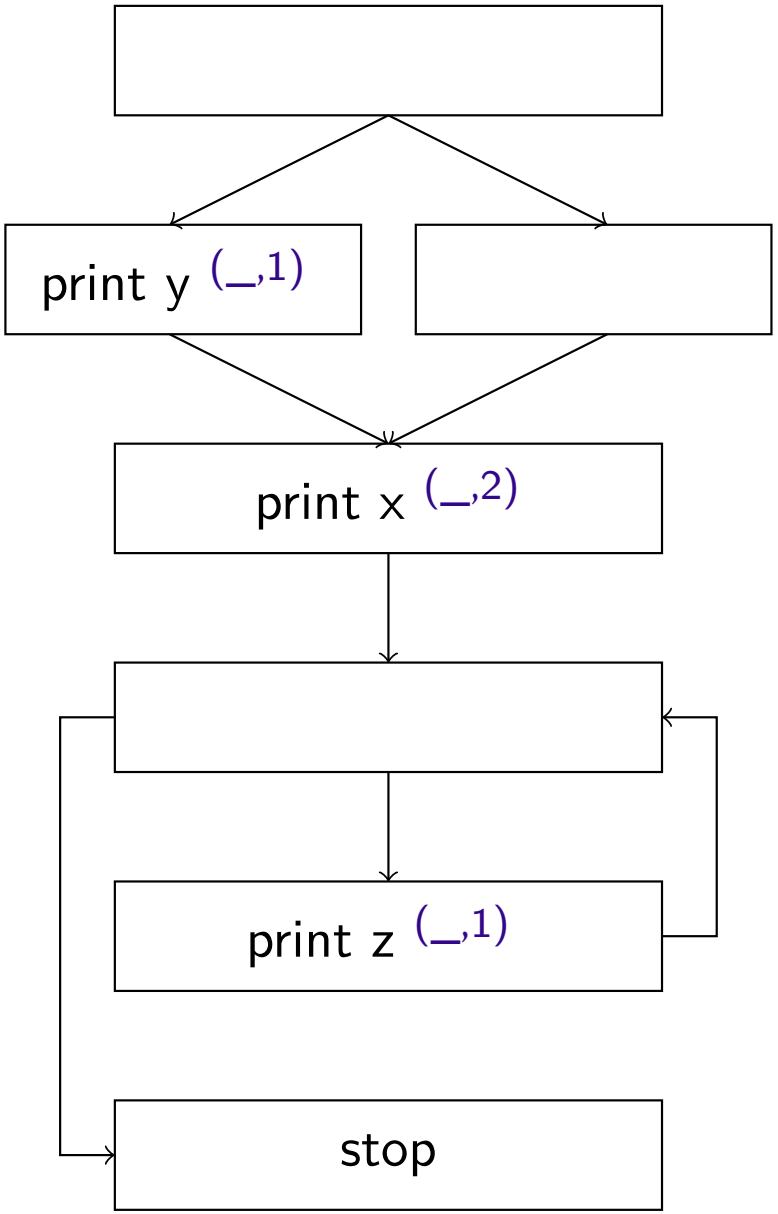
$$\mathscr{C} = \left(\mathscr{O}^1 \oplus \mathscr{O}^\epsilon\right)$$



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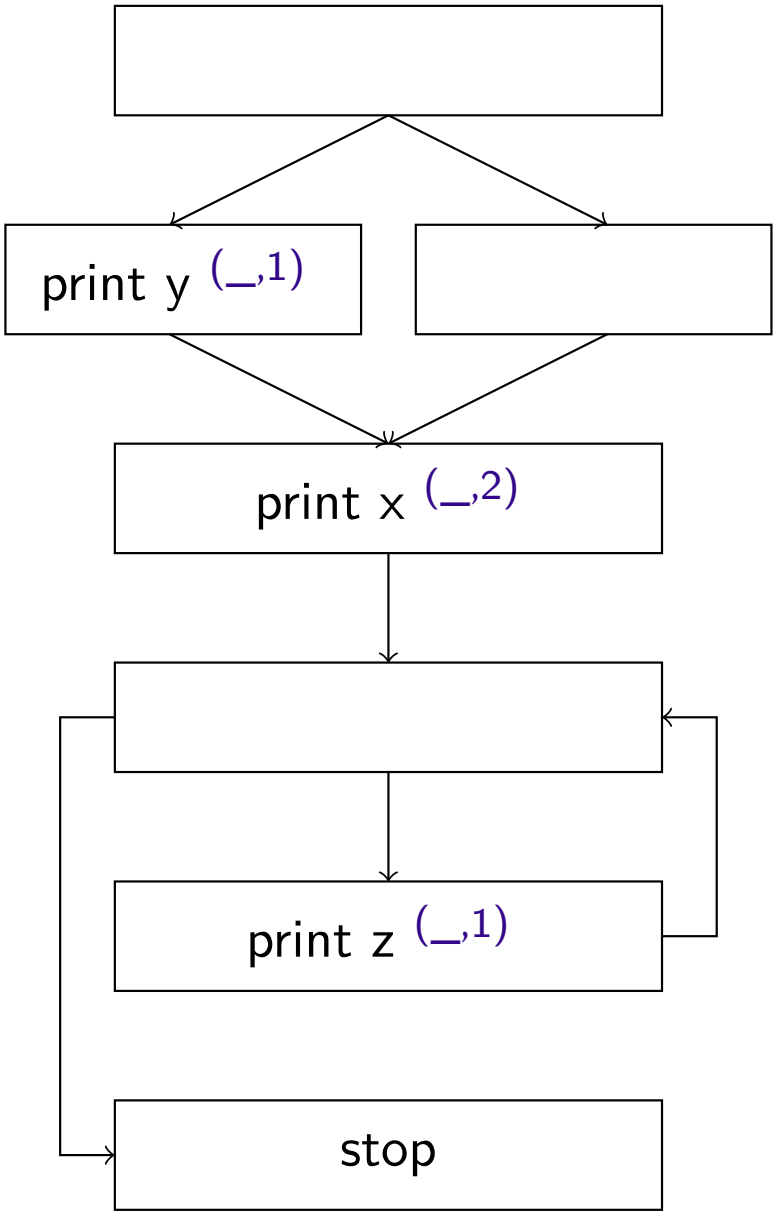
$$\mathscr{C} = \left(\mathscr{O}^1 \oplus \mathscr{O}^\epsilon\right) \cdot \mathscr{O}^2$$



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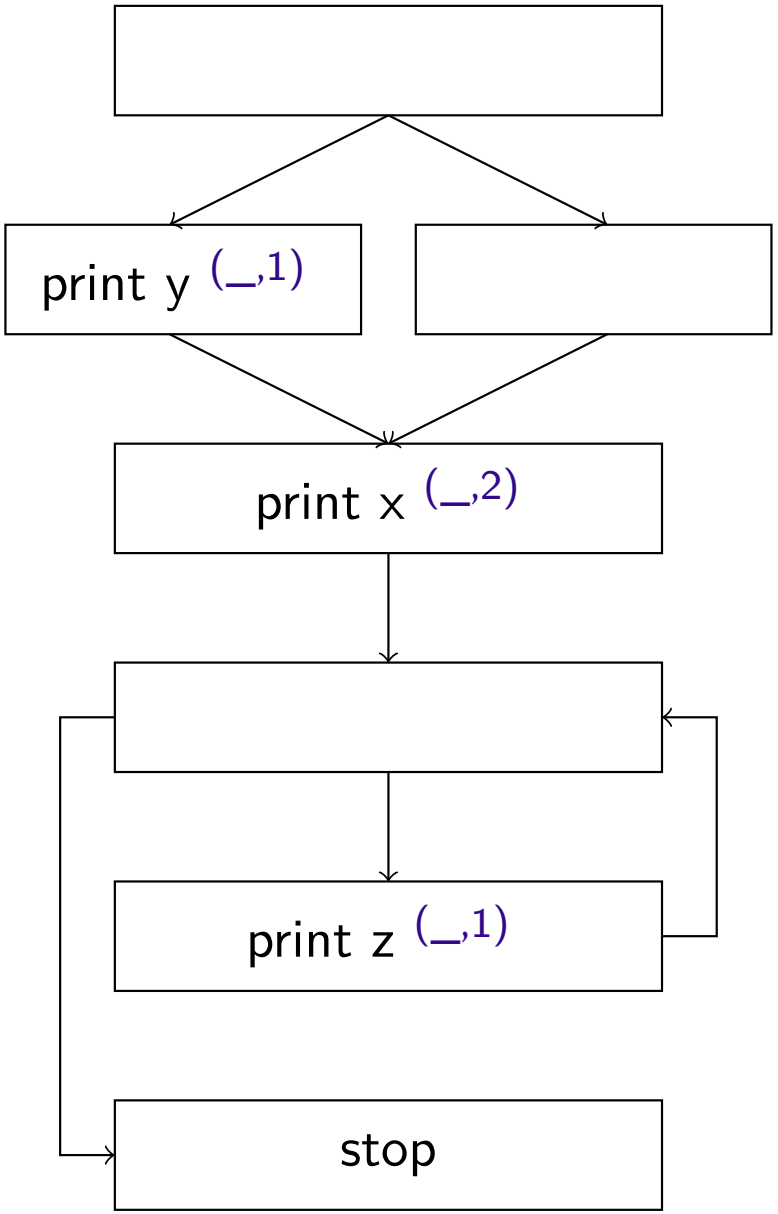

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$$\mathscr{C} = \left(\mathscr{O}^1 \oplus \mathscr{O}^\epsilon\right) \cdot \mathscr{O}^2 \cdot \left(\mathscr{O}^1\right)^\star \cdot \mathscr{O}^{\Uparrow}$$

- Relying on Analytic Combinatorics to systematically translate regular specifications into Ordinary Generating Functions (OGF) [Flajolet and Sedgewick,09]

$$\mathscr{C} = \left(\mathscr{O}^1 \oplus \mathscr{O}^\epsilon\right) \cdot \quad \mathscr{O}^2 \cdot \quad \left(\mathscr{O}^1\right)^\star \cdot \quad \mathscr{O}^{\Uparrow}$$

$$C(z) = (z+1) \cdot \quad 2z \cdot \quad \left(\frac{1}{1-z}\right) \cdot \quad z$$

- Extracting an asymptotic estimation of the leakage for polynomial time attackers by studying the singularities of the computed OGF
- Derived sufficient conditions on the OGF to prove Relative Secrecy

Qualitative IF

- `PWhile` Monitor : A sound hybrid information flow monitor supporting pointers and aliasing
- A sound inlining approach

Quantitative IF

- Relative Secrecy : Relaxing TINI while providing the same security guarantees wrt. polynomial time attackers
- Cardinal Abstraction : a sound analysis over-approximating the leakage for batch computations with public inputs
- Tree Abstraction : computing a regular specification of attackers' observations and deriving sufficient conditions to prove Relative Secrecy

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`PWhile` Monitor

Overcoming an inherent limitation of the inlining approach: casts, dynamic allocation...

Relative Secrecy

Improving both the cardinal abstraction and the tree abstraction by combining different abstract domains :

- Numerical abstractions
- Selective Trace Partitioning
- Relational abstraction [Miné,06]

Dreams

Hold fast to dreams
For if dreams die
Life is a broken-winged bird
That cannot fly.

Hold fast to dreams
For when dreams go
Life is a barren field
Frozen with snow.

Langston Hughes