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Taming Undefined Behavior in LLVM

Seoul National Univ.	**Juneyoung Lee** Yoonseung Kim Youngju Song Chung-Kil Hur
Azul Systems	Sanjoy Das
Google	David Majnemer
University of Utah	John Regehr
Microsoft Research	Nuno P. Lopes

What this talk is about

- A compiler IR (Intermediate Representation) can be designed to allow more optimizations by supporting "undefined behaviors (UBs)"
- LLVM IR's UB model
  - Complicated
  - Invalidates some textbook optimizations
- Our new UB model
  - Simpler
  - Can validate textbook optimizations (and more)

Undefined Behavior (UB) & Problems

Motivation for UB

Peephole Optimization

```
int* p
int  a
int  b
```

IR

```
output(p + a > p + b)
```

IR

```
output(a > b)
```

Motivation for UB

Peephole Optimization

```
int* p
int  a
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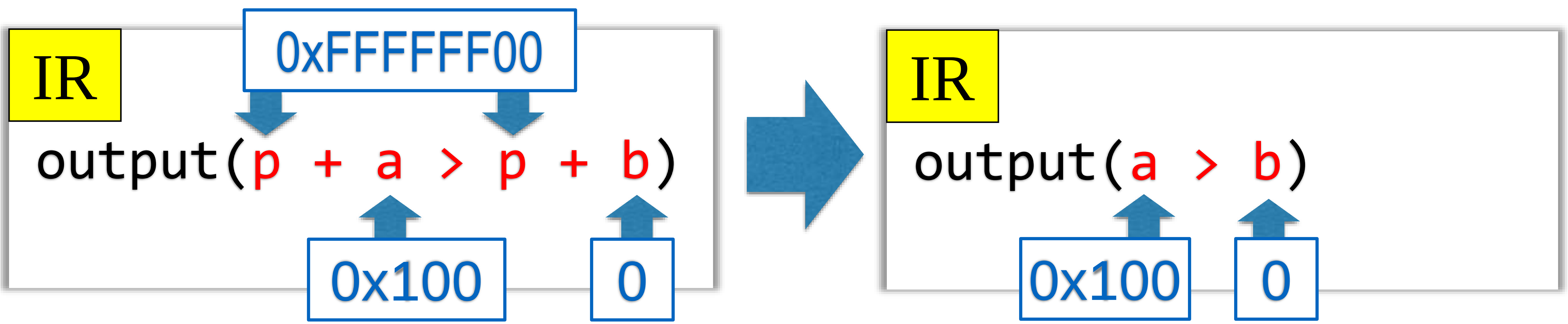
```



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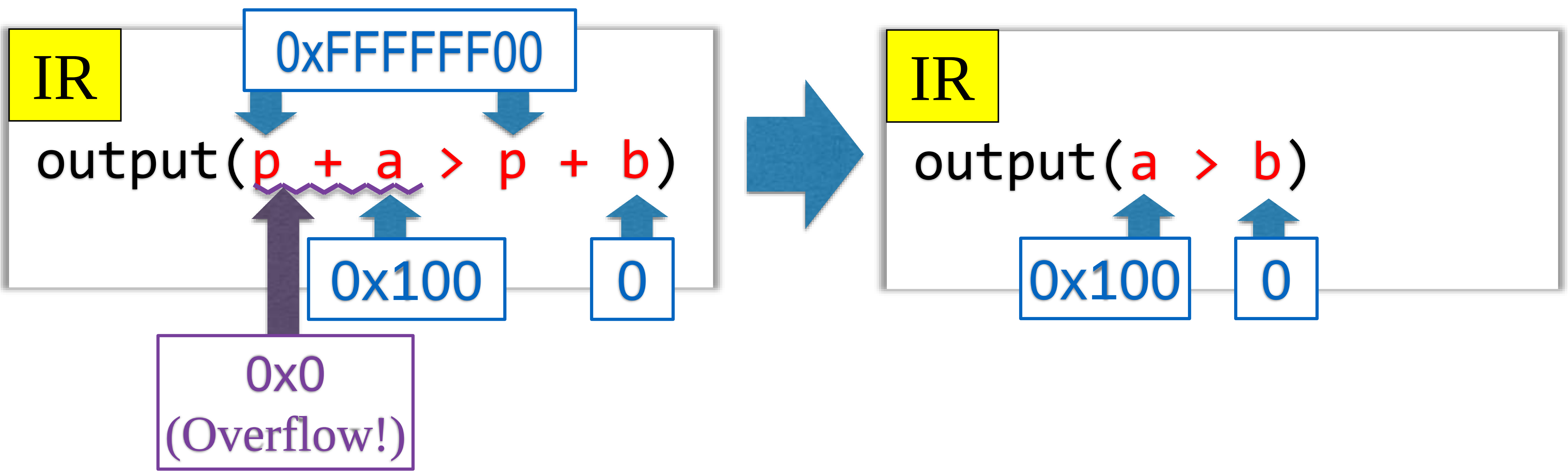

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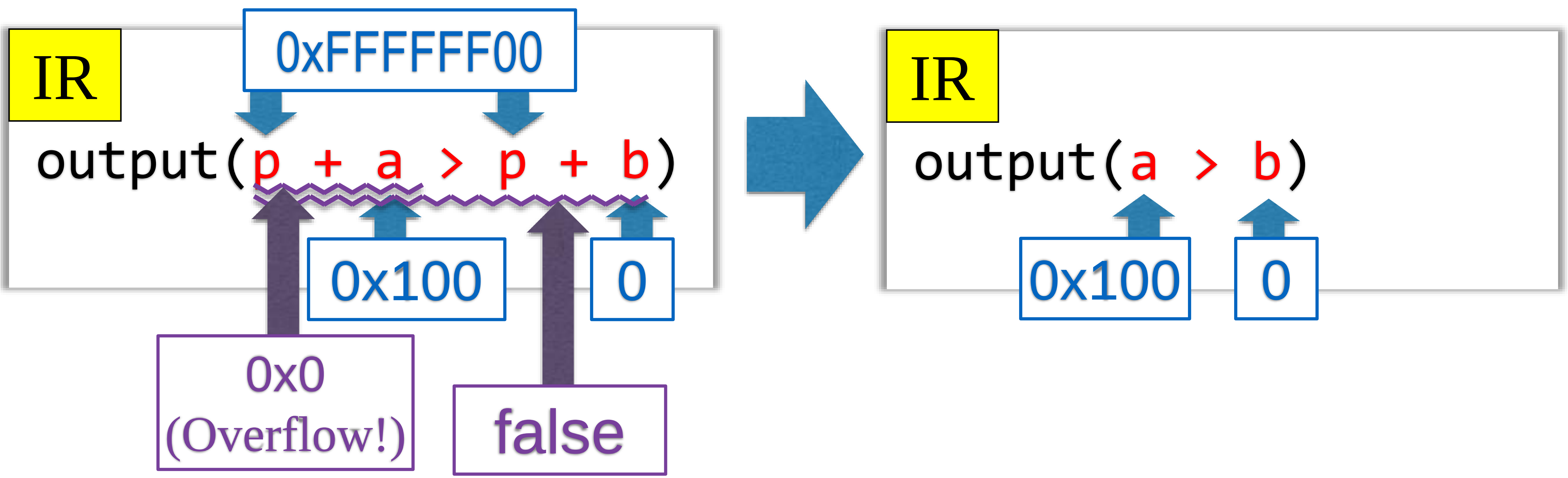

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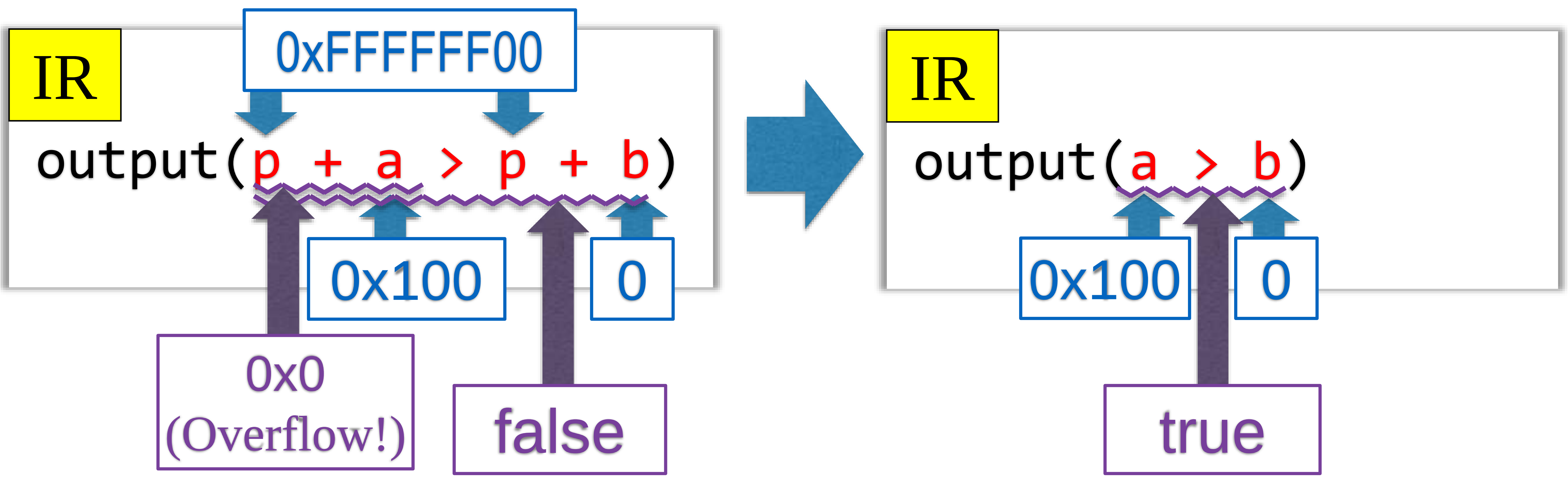

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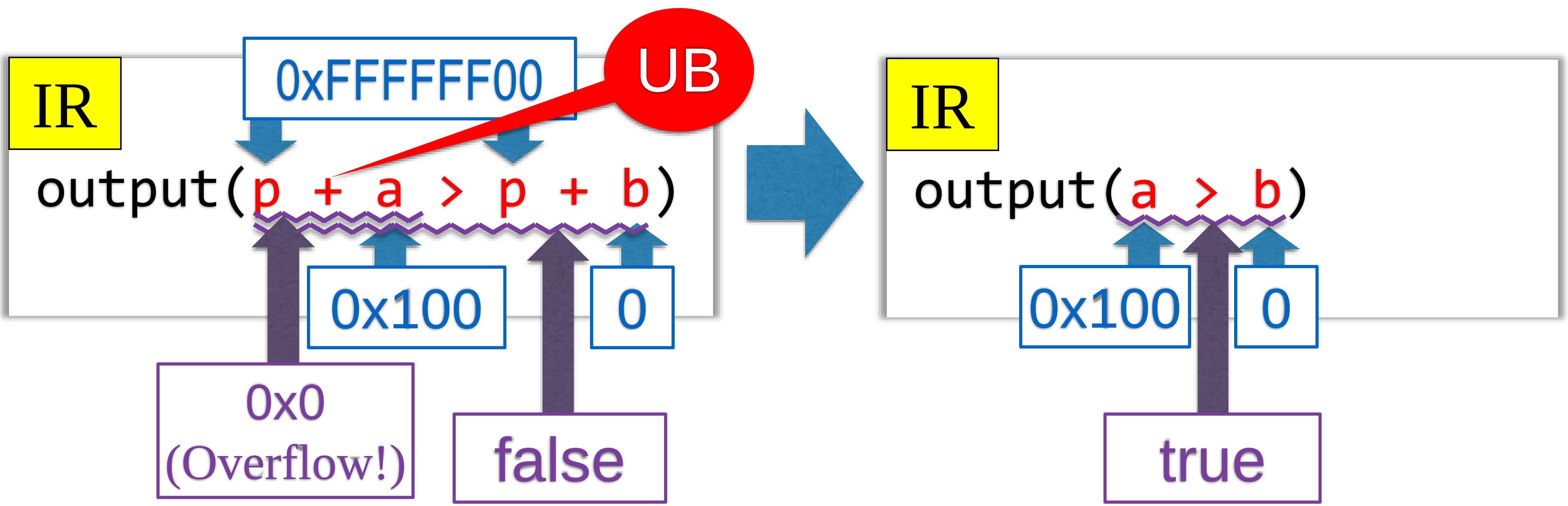
Peephole Optimization

Simple UB Model:

Pointer Arithmetic Overflow is

Undefined Behavior



Problems with UB

Loop Invariant Code Motion

Simple UB Model:

Pointer Arithmetic Overflow is

Undefined Behavior

IR

```
...
for(i=0; i<n; ++i)
{
  a[i] = p + 0x100
}
```

IR

```
q = p + 0x100
for(i=0; i<n; ++i)
{
  a[i] = q
}
```

Problems with UB

Loop Invariant Code Motion

Simple UB Model:

Pointer Arithmetic Overflow is

Undefined Behavior

IR

0

```
...
for(i=0; i<n; ++i)
{
  a[i] = p + 0x100
}
```

0xFFFFFF00

0xFFFFFF00

IR

```
q = p + 0x100
for(i=0; i<n; ++i)
{
  a[i] = q
}
```

0

Loop Invariant Code Motion

Simple UB Model:

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Overflow!

IR

```
q = p + 0x100
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}
```

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Problems with UB

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```
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for(i=0; i<n; ++i)
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IR

Overflow!

UB

```
q = p + 0x100
for(i=0; i<n; ++i)
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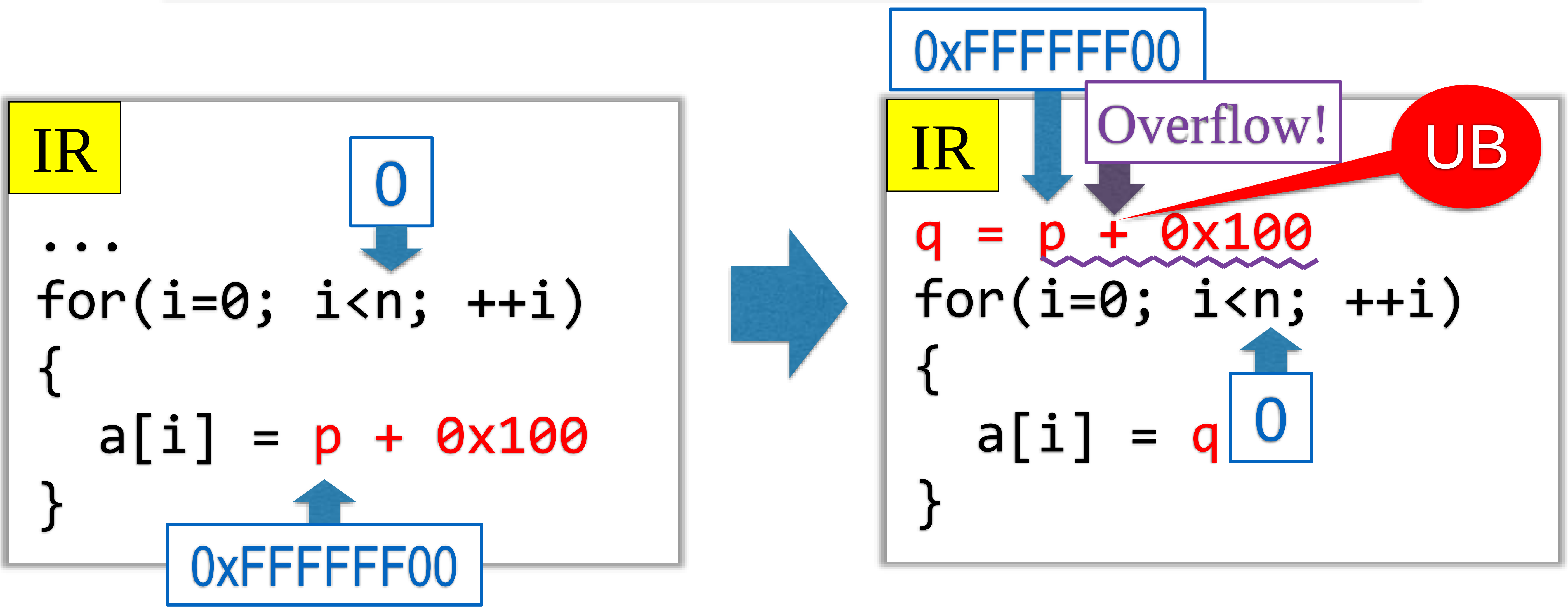
Existing Approaches

Poison Value: A Deferred UB

Simple UB Model:
Pointer Arithmetic Overflow is
Undefined Behavior

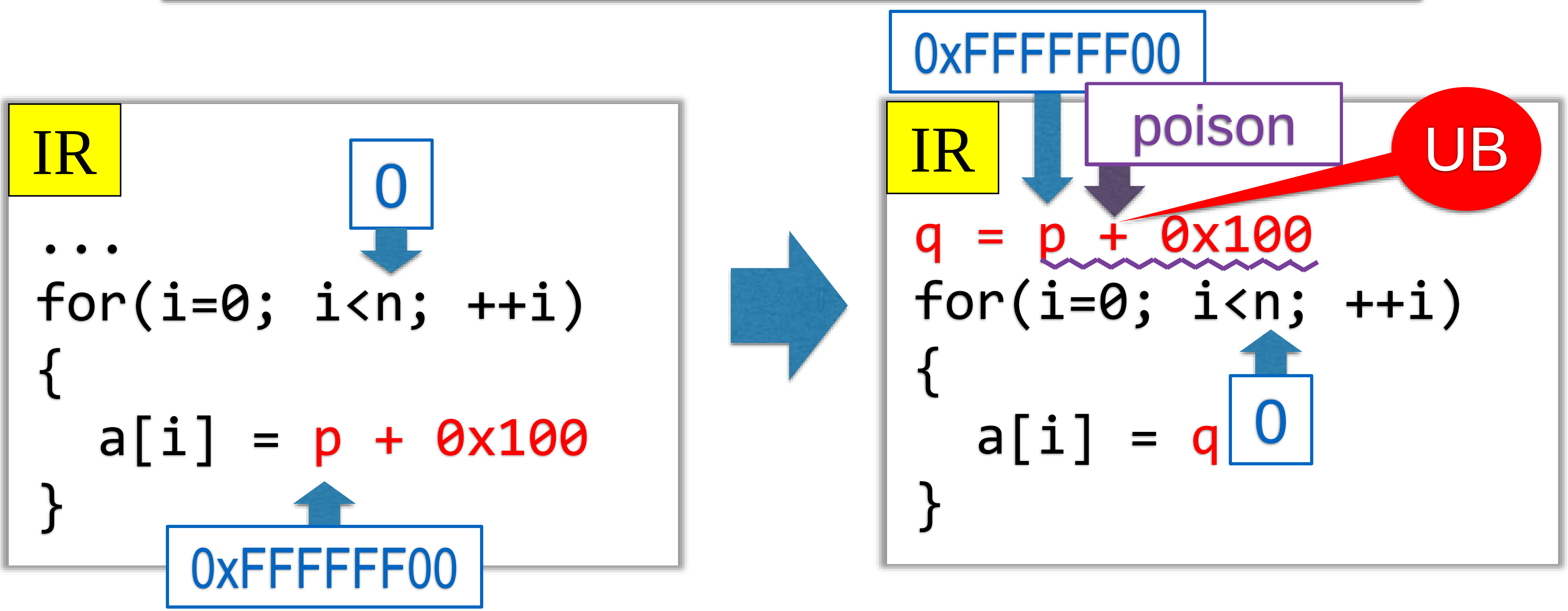


Poison Value: A Deferred UB

LLVM's UB Model:

Pointer Arithmetic Overflow is

A Poison "Value"



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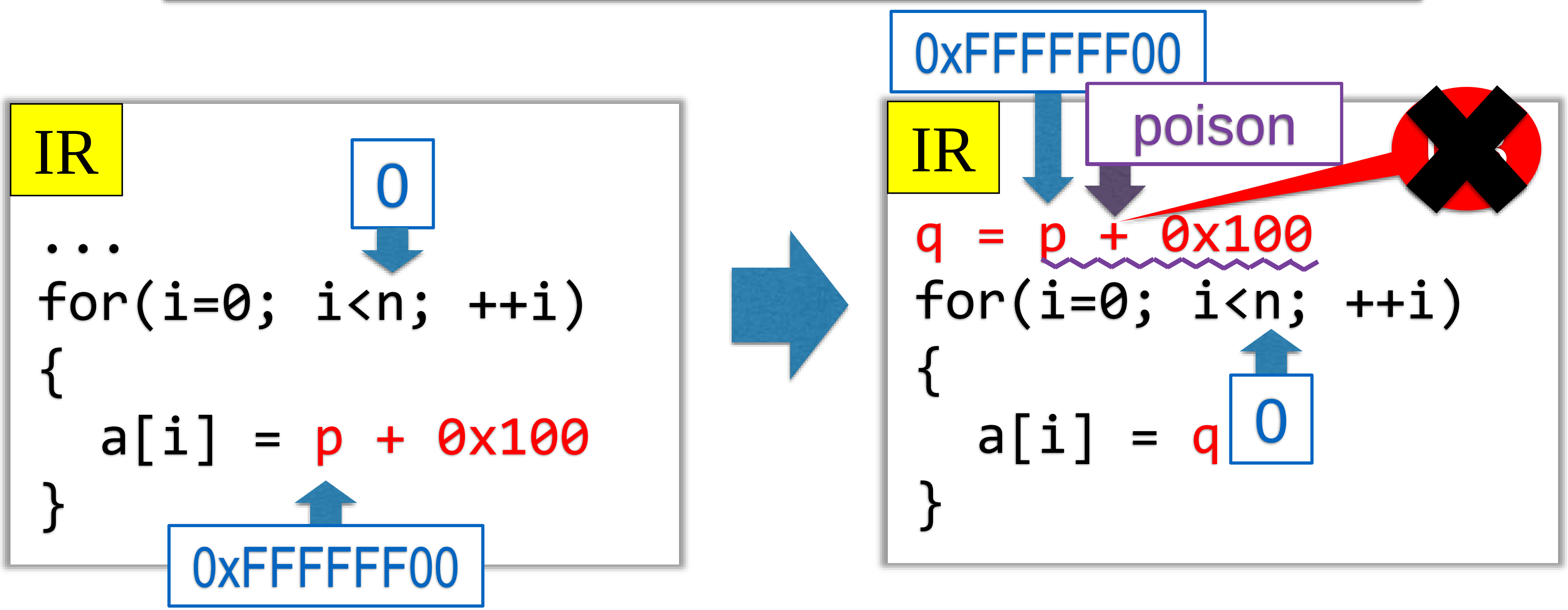

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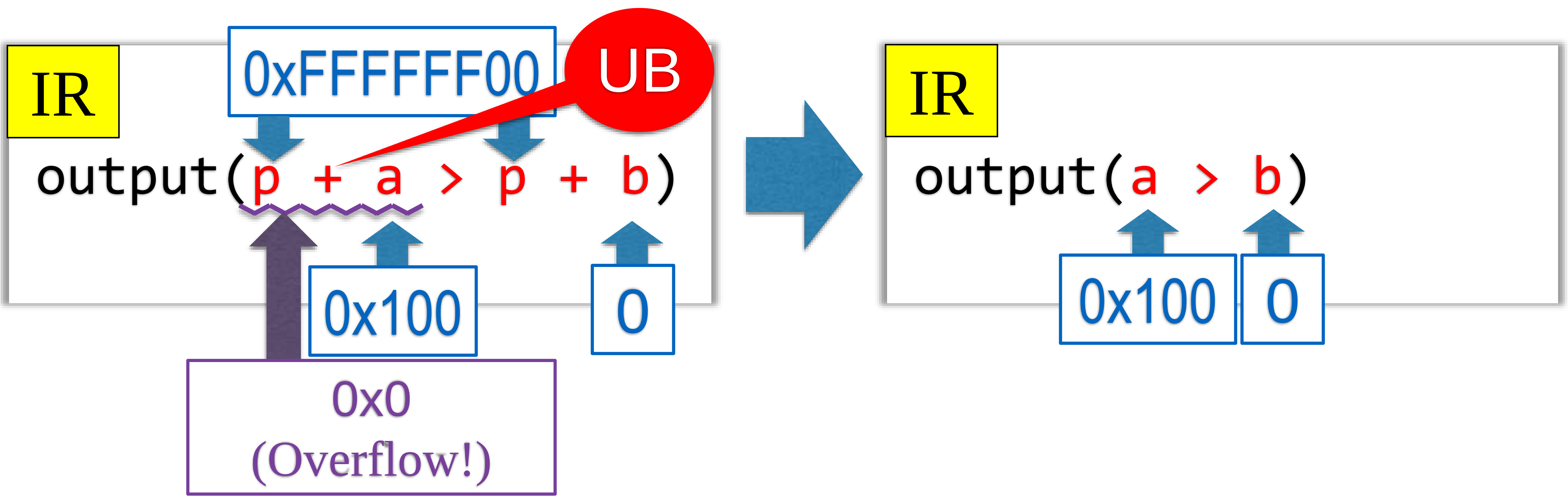

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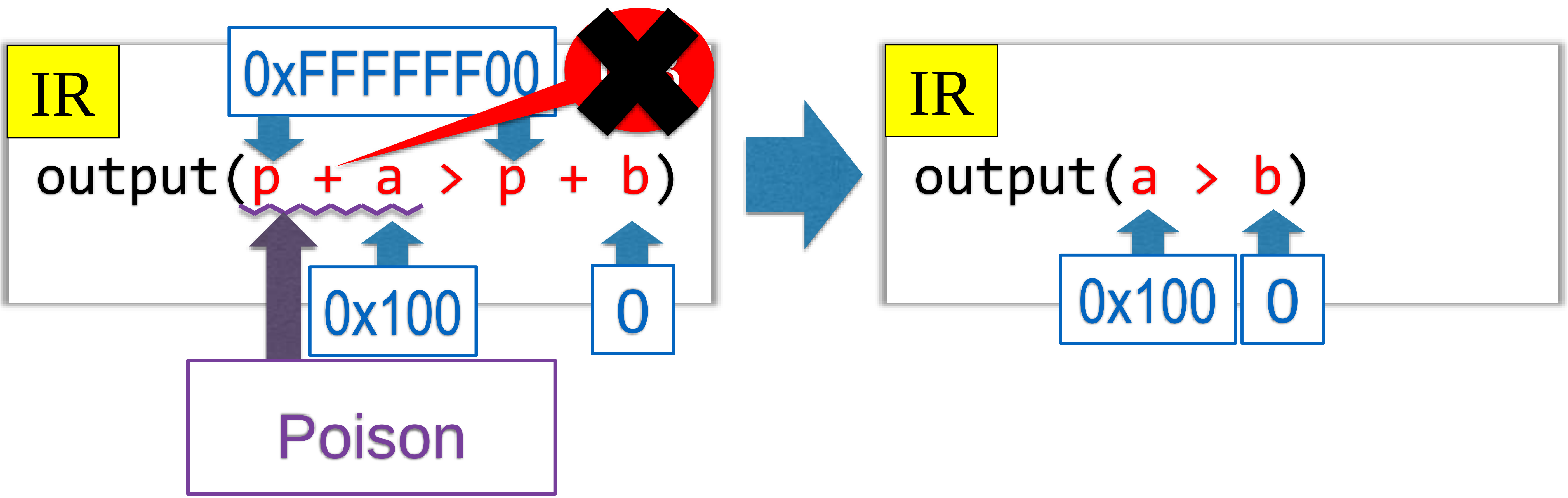

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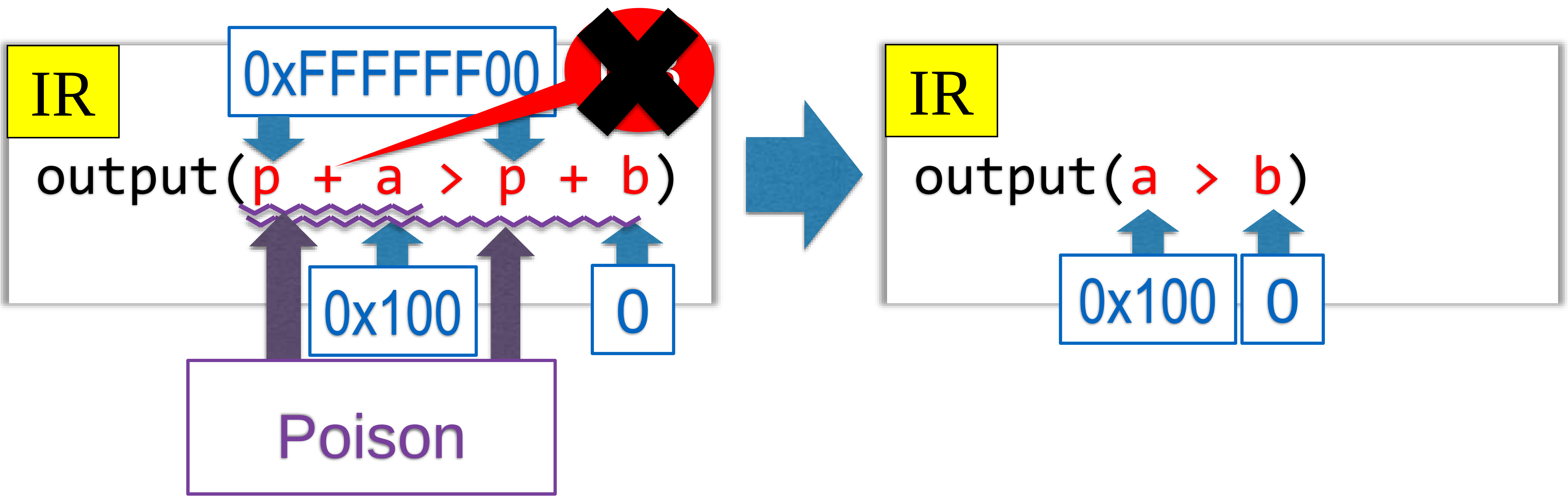

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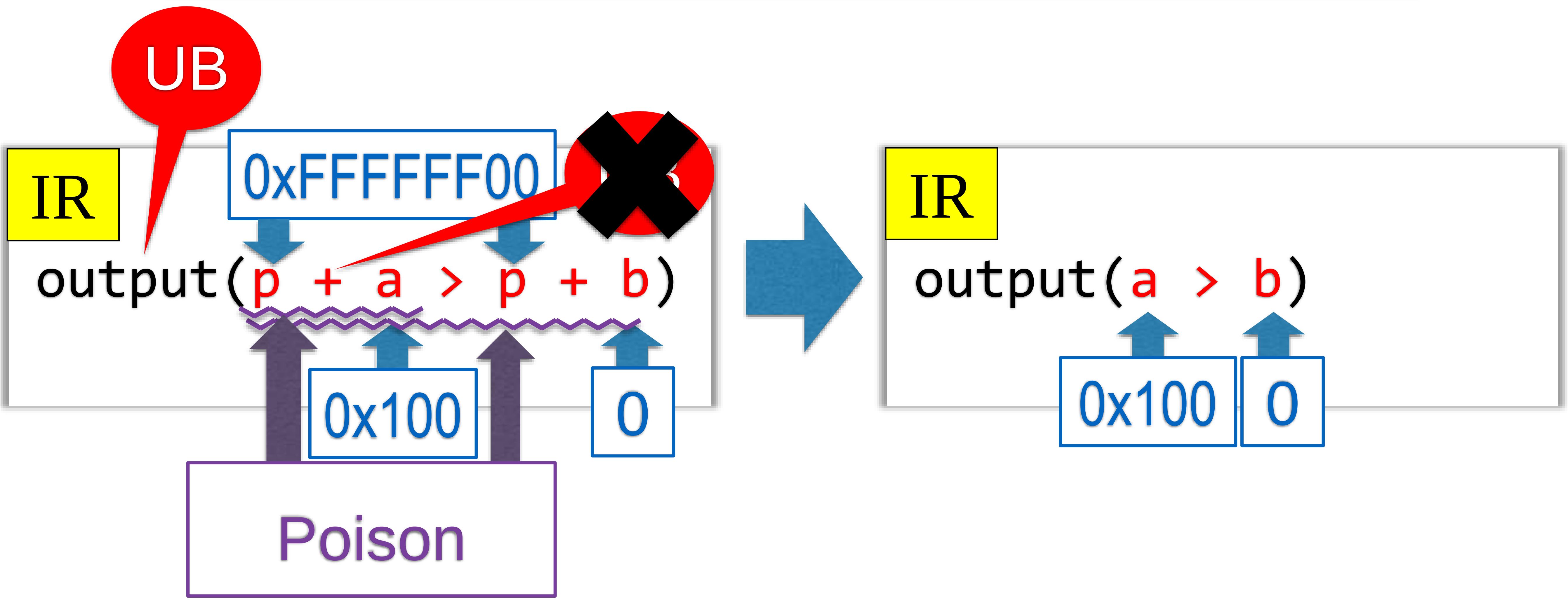
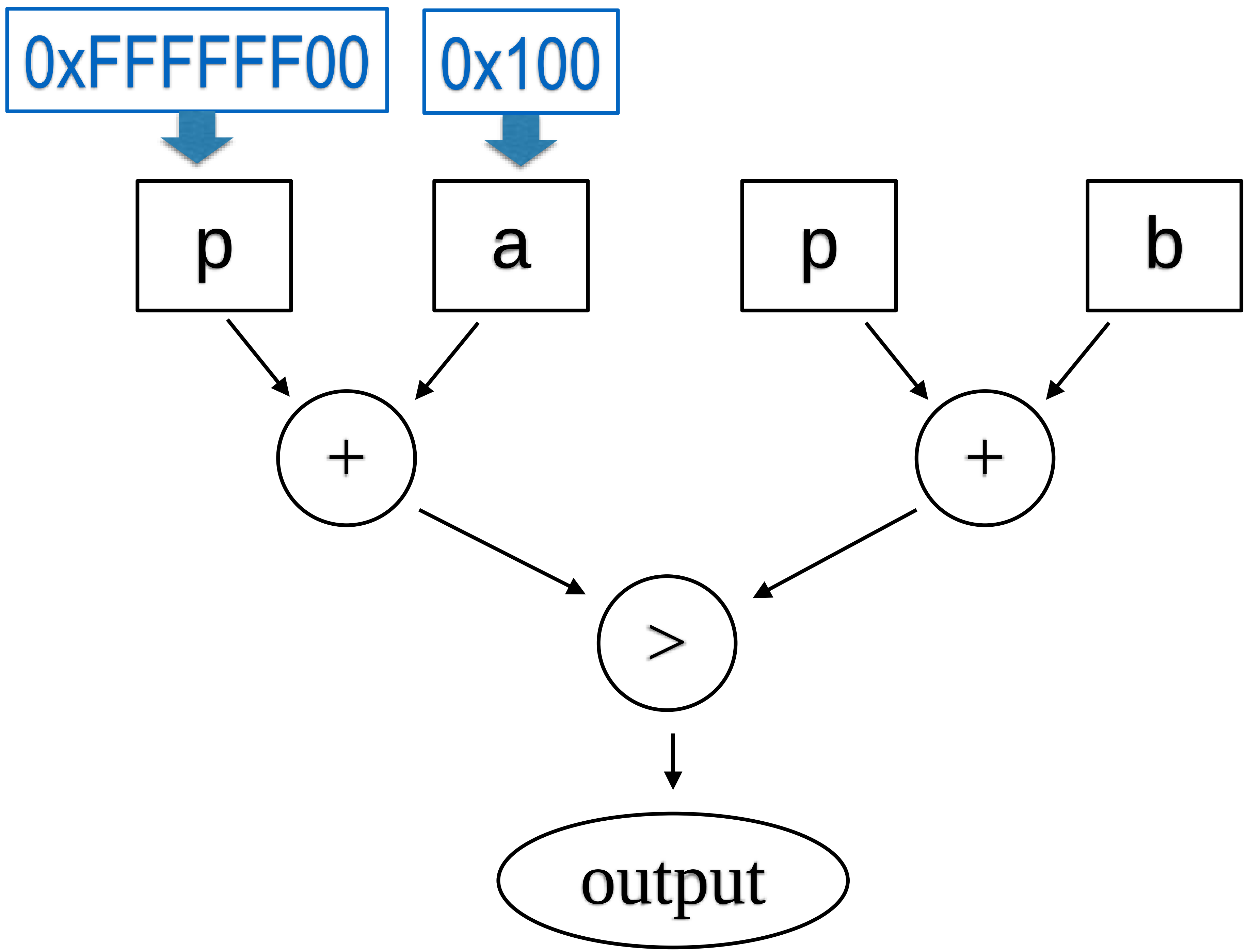


Summary of Poison



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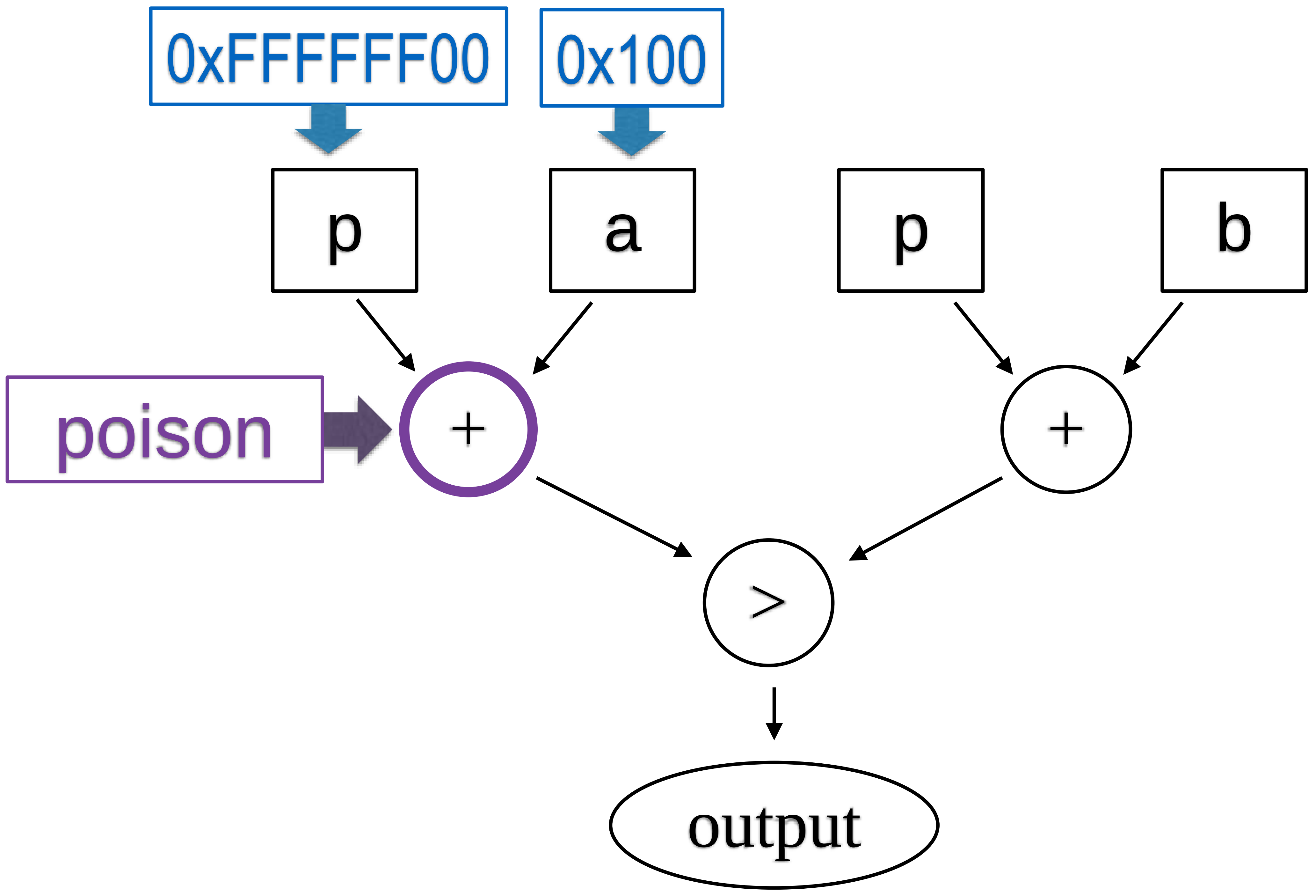

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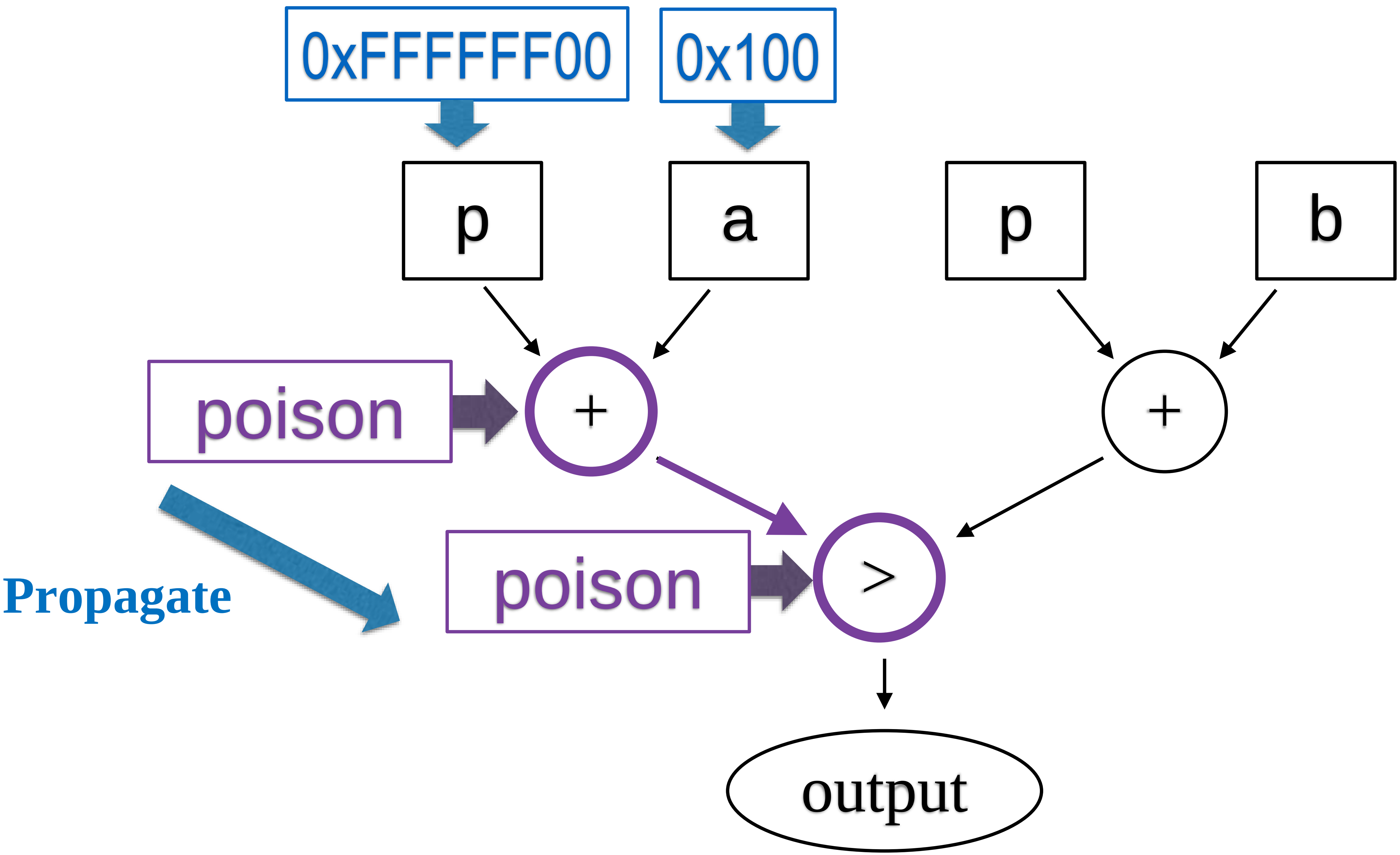

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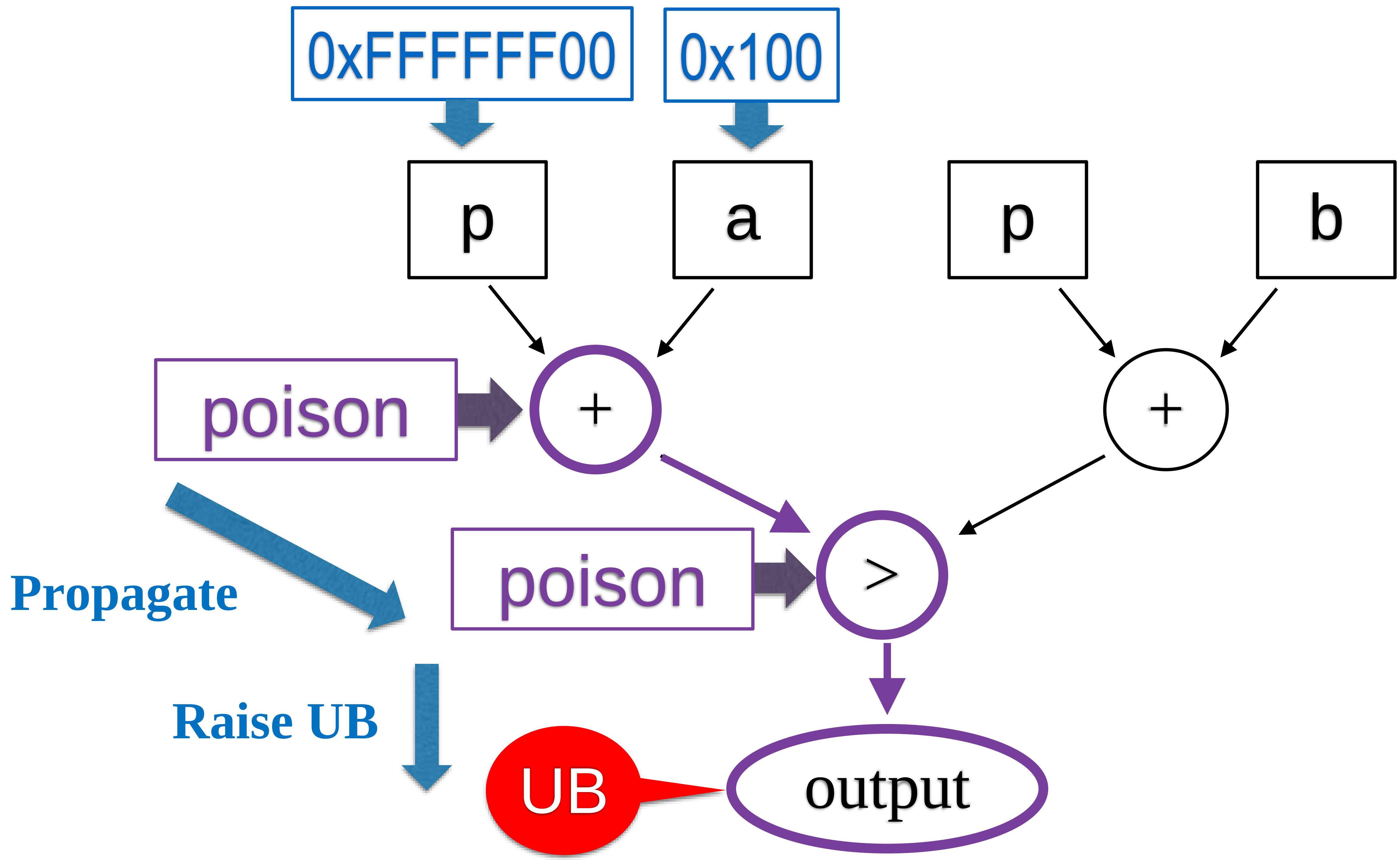

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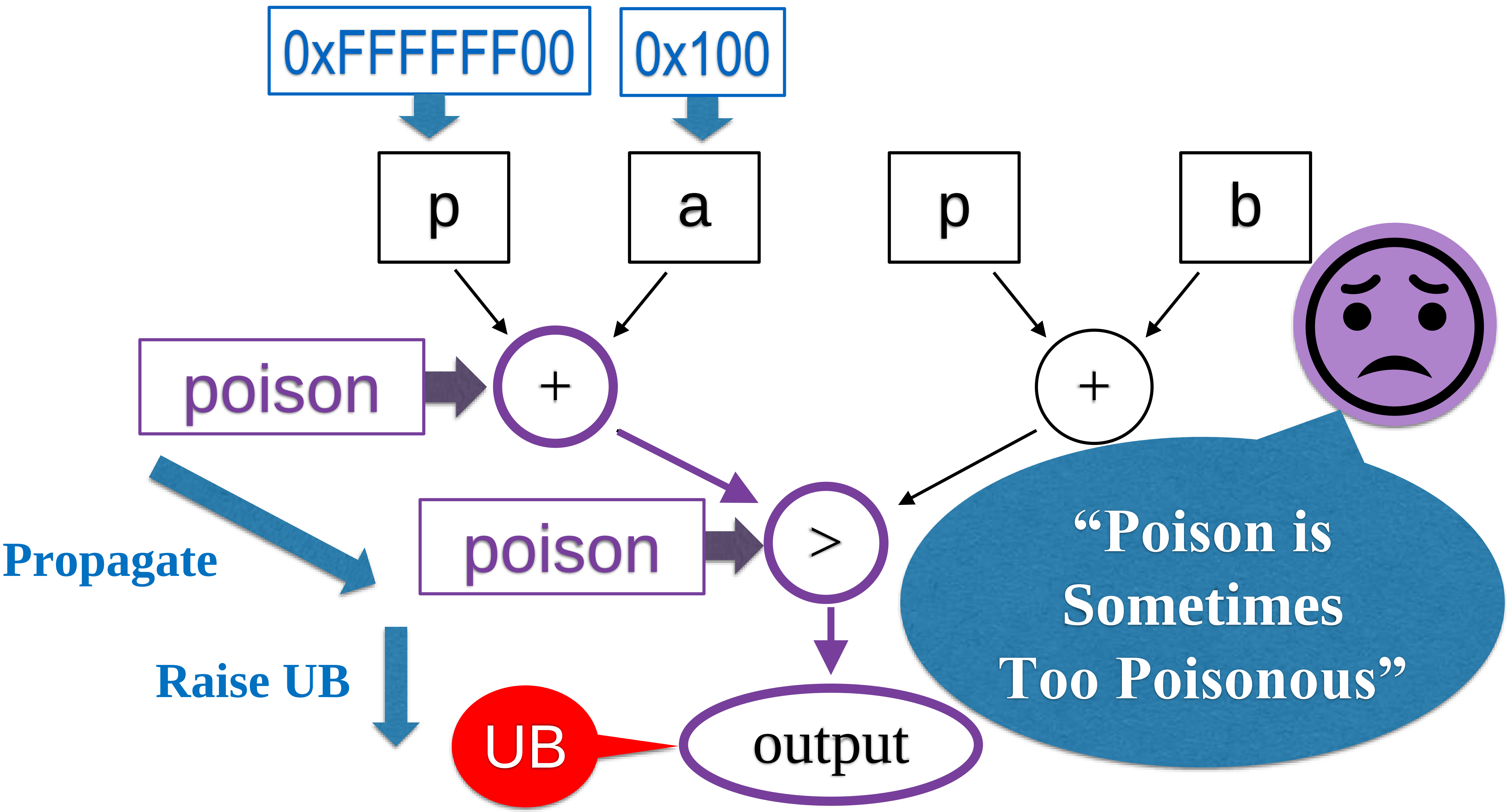

Problems with LLVM's UB

Global Value Numbering (GVN)

LLVM's UB Model:

Branching on poison is

???

```
if (x == y) {

  .. use x ..

}
```

```
if (x == y) {

  .. use y ..

}
```

Problems with LLVM's UB

Global Value Numbering (GVN)

LLVM's UB Model:

Branching on poison is

???

0 poison

```
if (x == y) {

  .. use x ..

}
```

0 poison

```
if (x == y) {

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```

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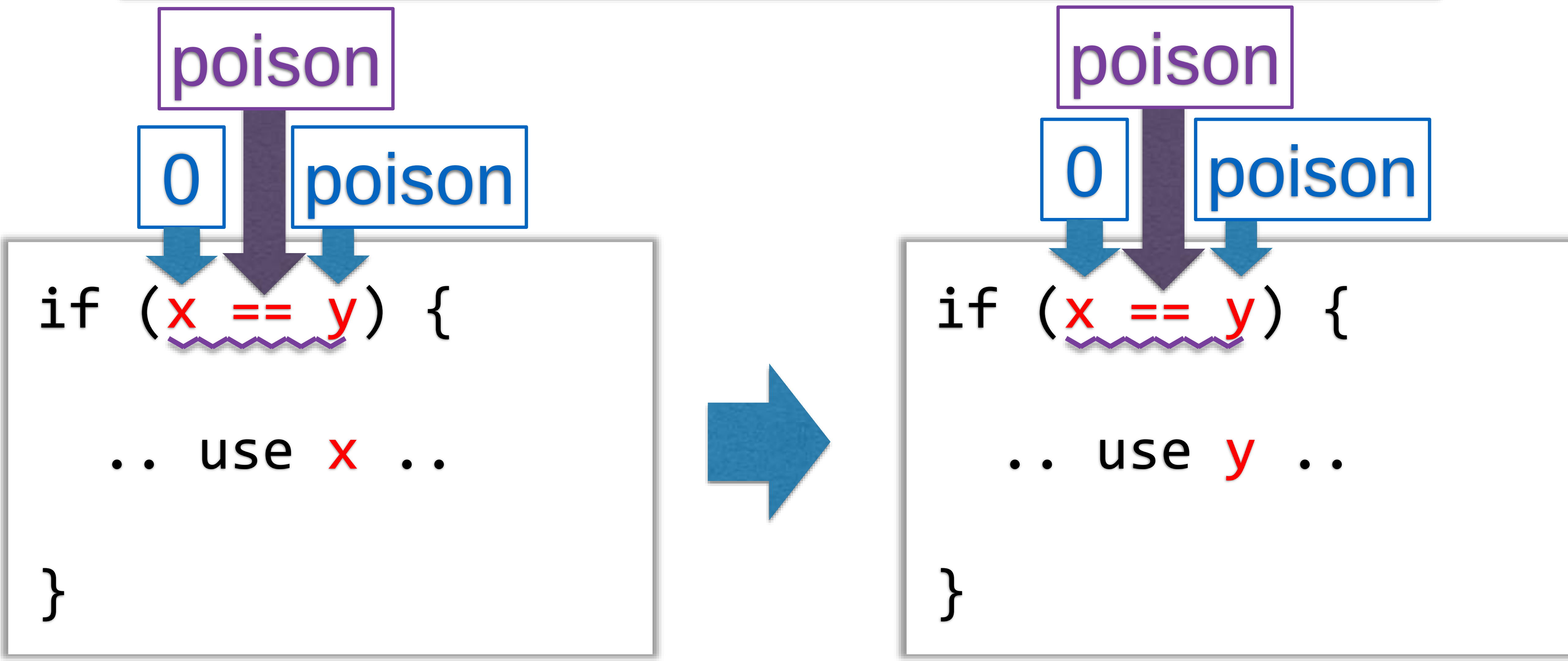

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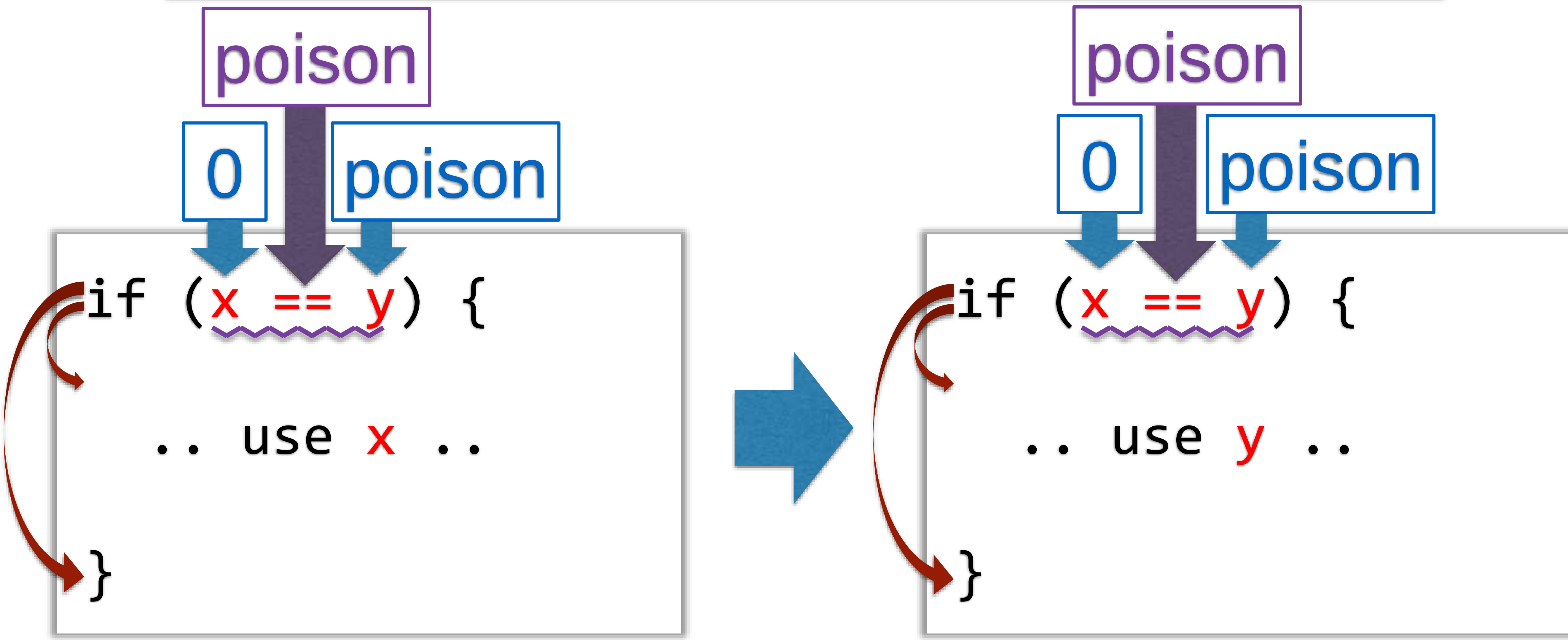

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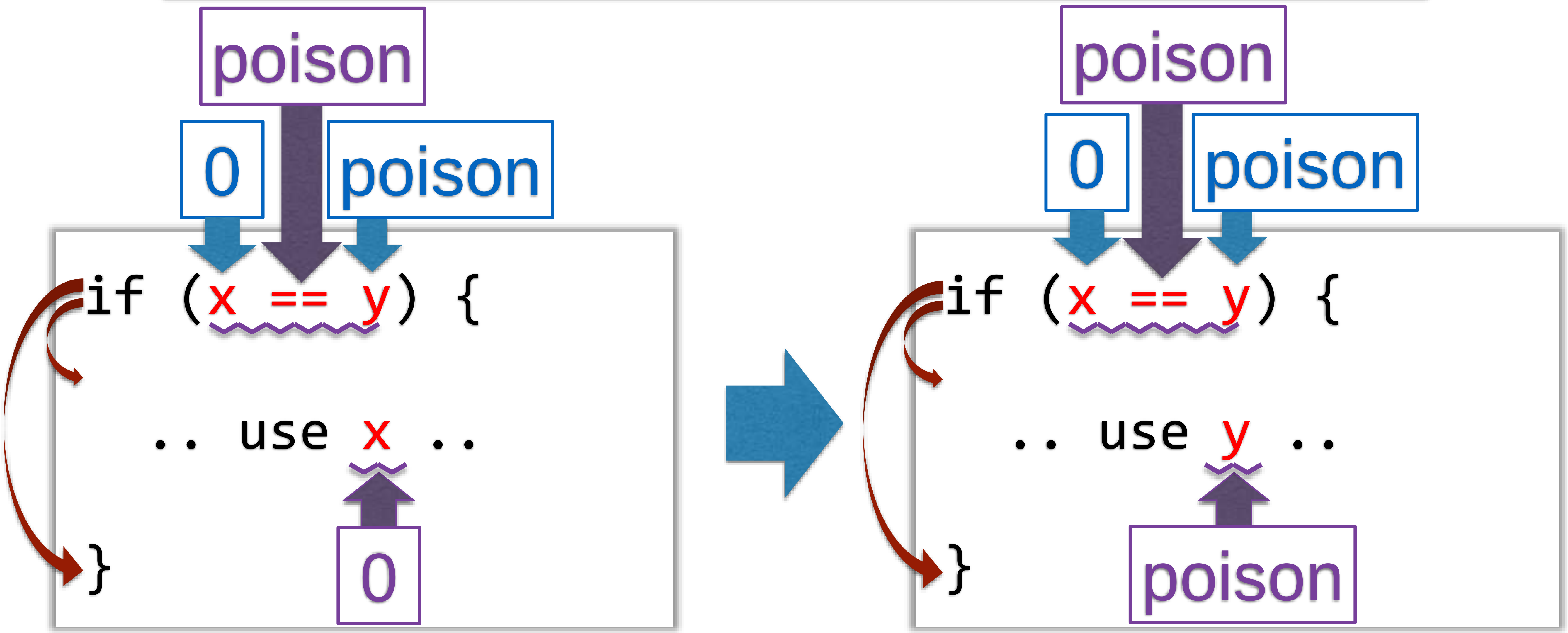

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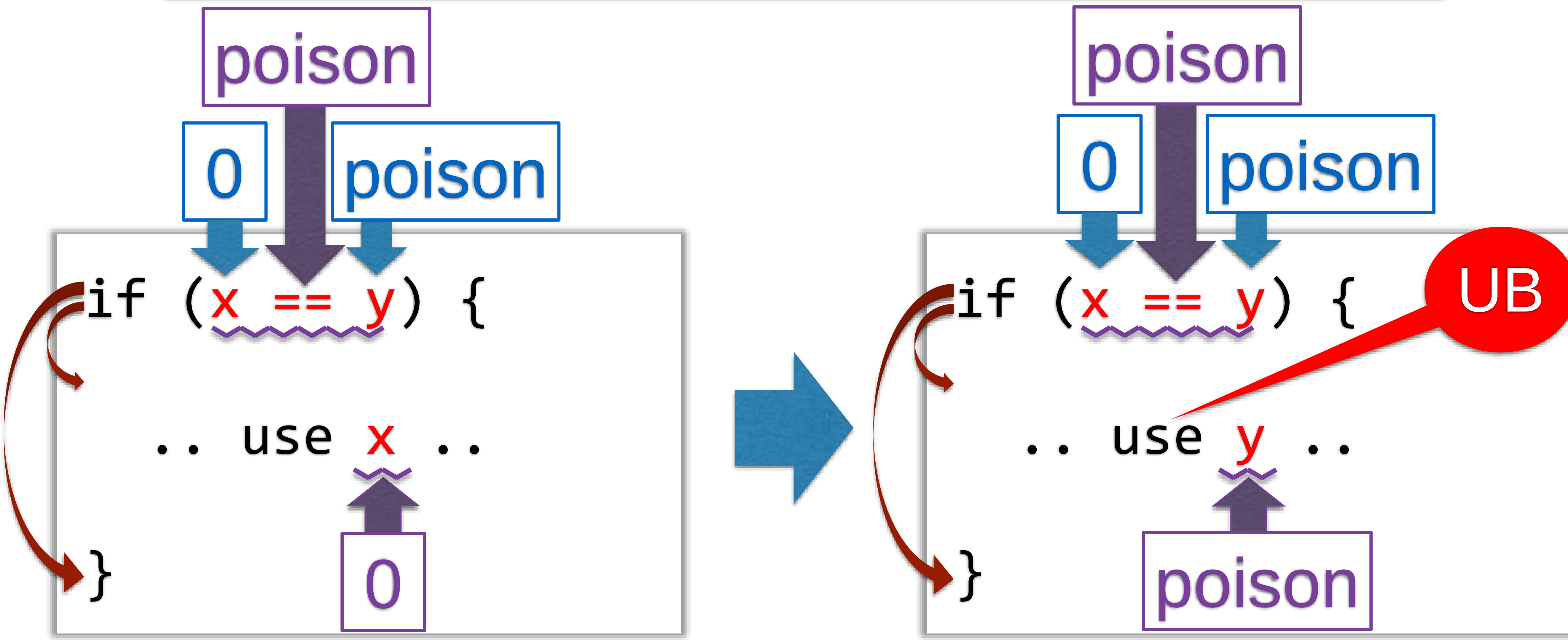
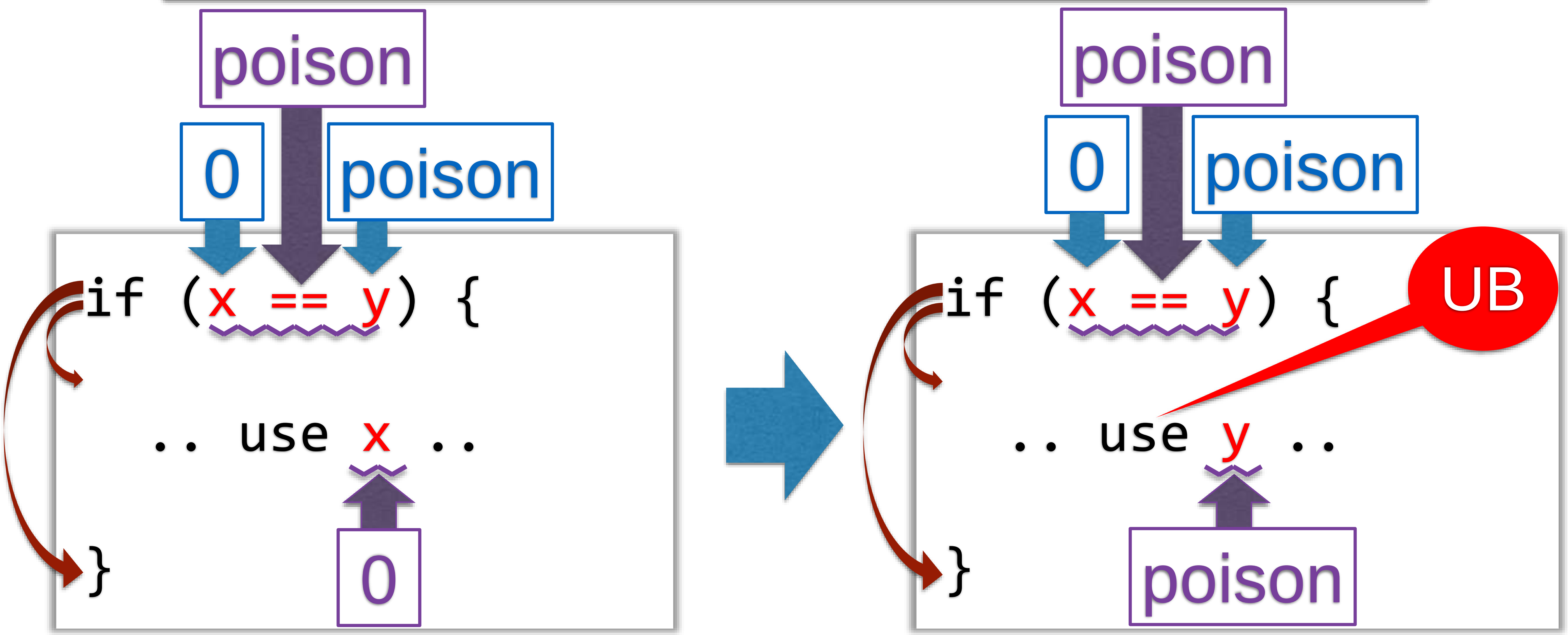


Global Value Numbering (GVN)

LLVM's UB Model:
Branching on poison is
Undefined Behavior



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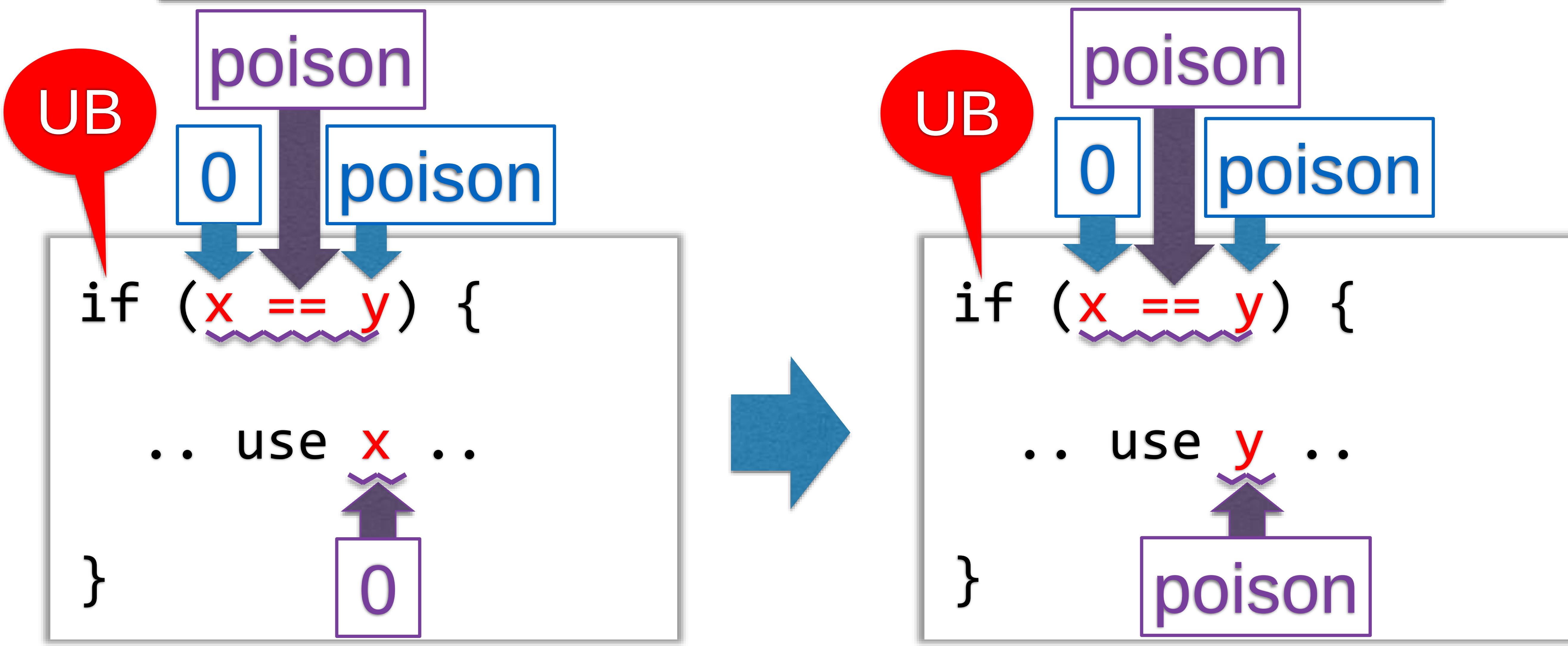


Problems with LLVM's UB

Loop Unswitching (LU)

LLVM's UB Model:
Branching on poison is
Undefined Behavior

```
while (n > 0) {
  if (cond)
    A
  else
    B
}
```

```
if (cond)
  while (n > 0)
  { A }
else
  while (n > 0)
  { B }
```

Problems with LLVM's UB

Loop Unswitching (LU)

LLVM's UB Model:

Branching on poison is

Undefined Behavior

0

poison

```
while (n > 0) {
  if (cond)
    A
  else
    B
}
```

poison

0

```
if (cond)
  while (n > 0)
  { A }
else
  while (n > 0)
  { B }
```

Problems with LLVM's UB

Loop Unswitching (LU)

LLVM's UB Model:

Branching on poison is

Undefined Behavior

0

```
while (n > 0) {
  if (cond)
    A
  else
    B
}
```

poison

UB

poison

```
if (cond)
  while (n > 0)
  { A }
else
  while (n > 0)
  { B }
```

0

Inconsistency in LLVM

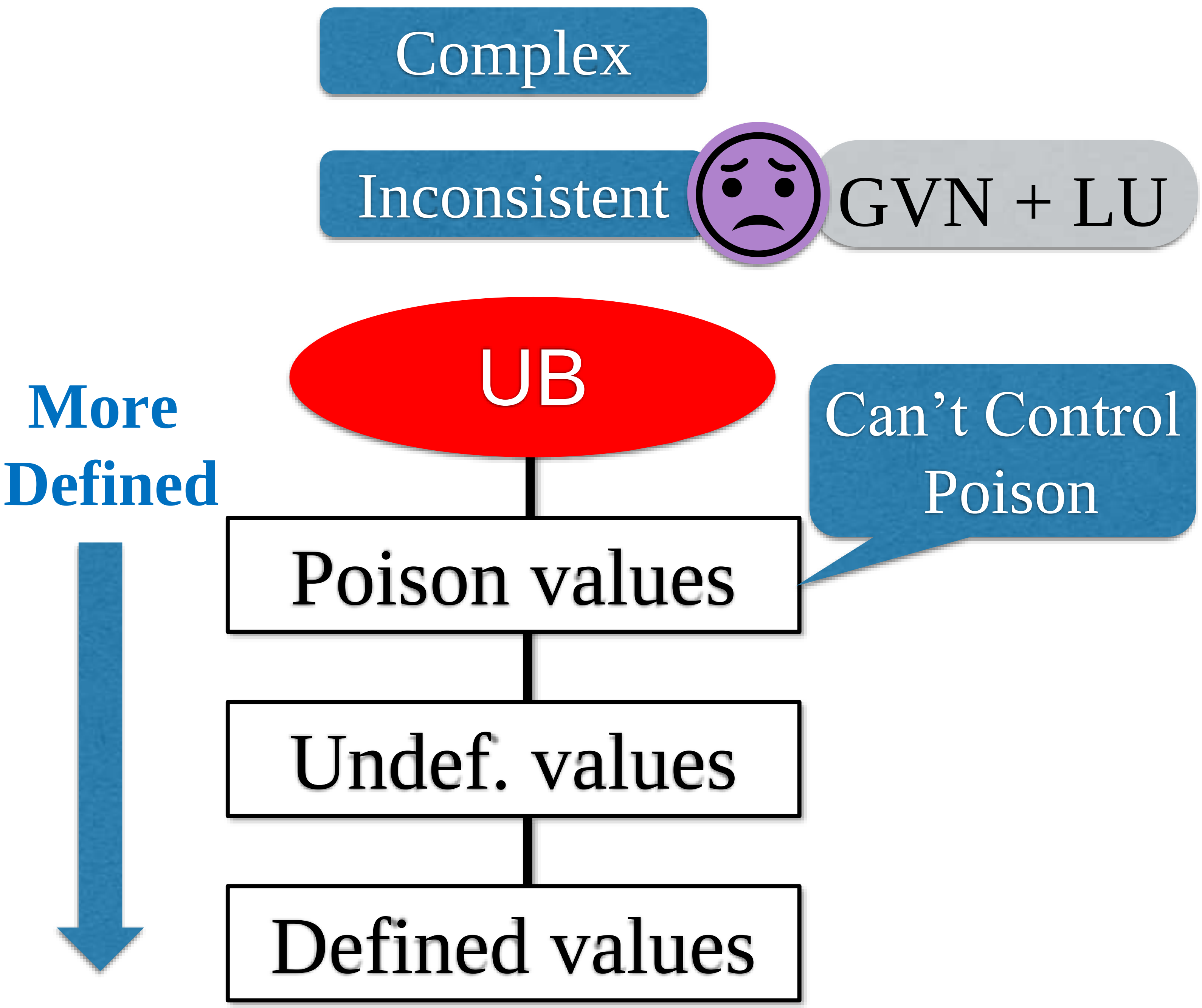
- GVN + LU is inconsistent.

- We found a miscompilation bug in LLVM due to the inconsistency (LLVM Bugzilla 31652).
  - It is being discussed in the community
  - No solution has been found yet

Our Approach

Overview

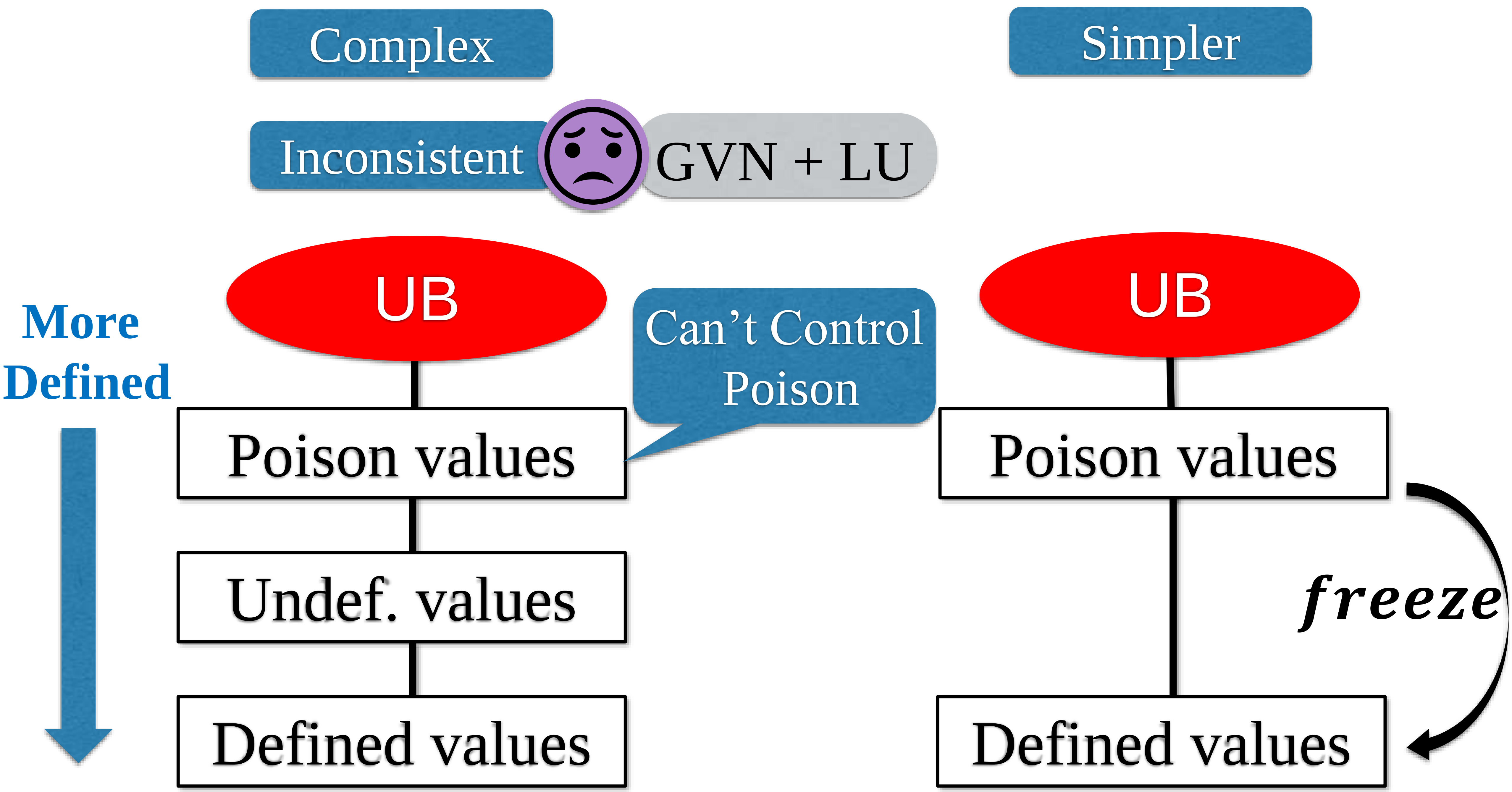
Existing Approaches



Overview

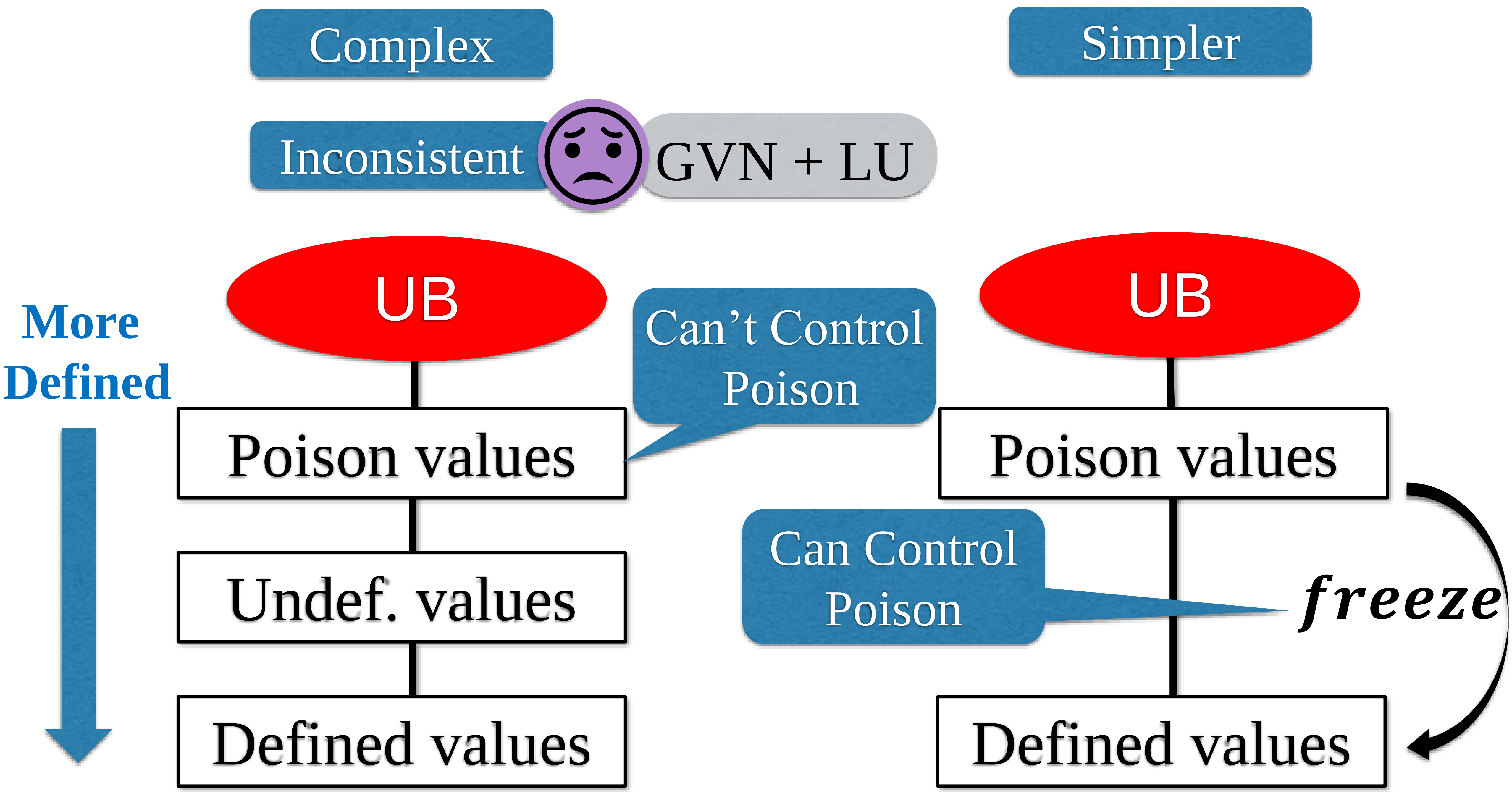
Existing Approaches

Our Approach



Overview

Existing Approaches | **Our Approach**



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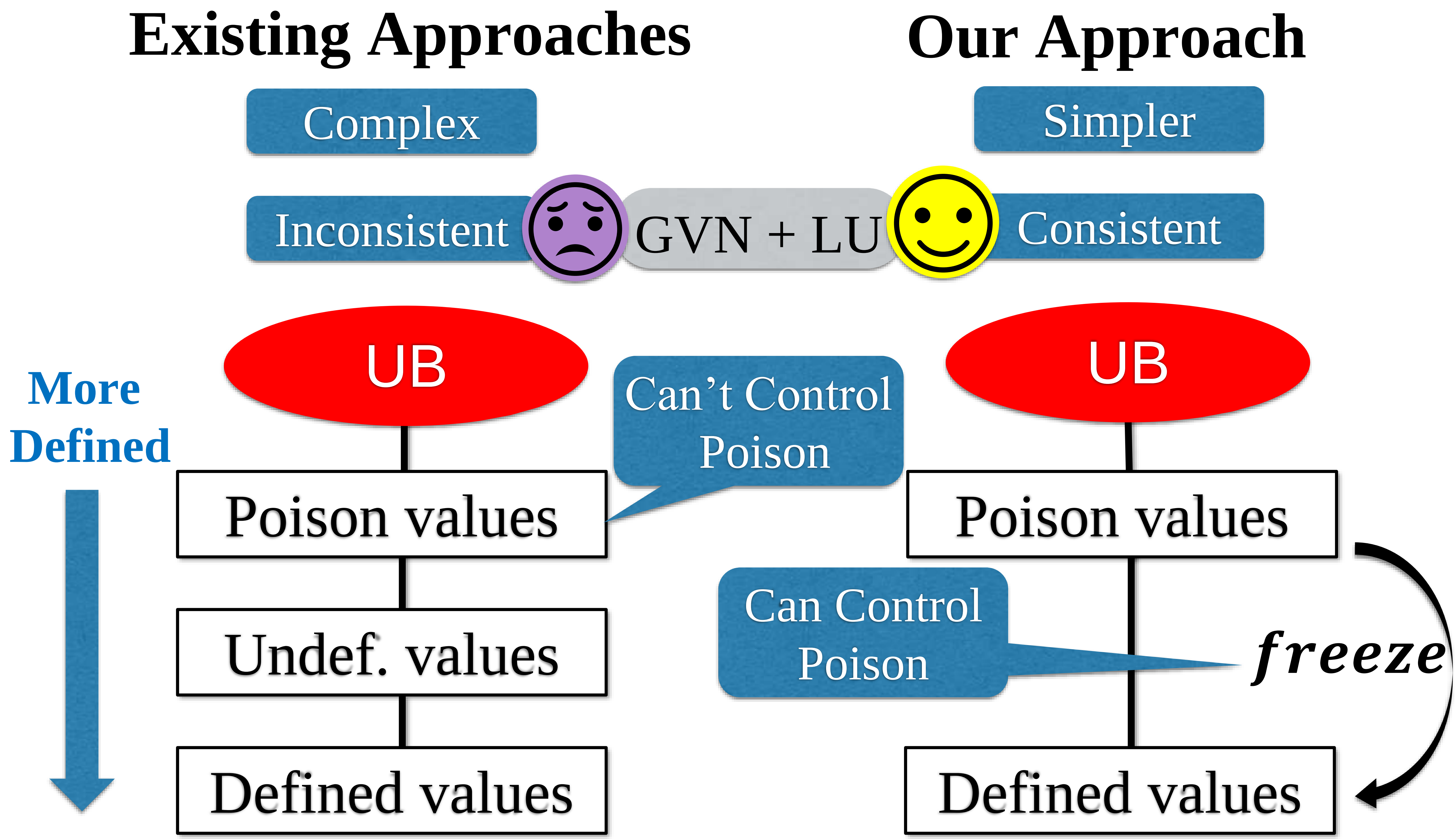
Existing Approaches
Our Approach
Complex
Simpler
Inconsistent
GVN + LU
Consistent
UB
UB
More
Defined
Can't Control
Poison
Poison values
Undef. values
Defined values
Poison values
Can Control
Poison
freeze
Defined values

Key Idea: "Freeze"

- Introduce a new instruction

```
y = freeze x
```

- Semantics:

When `x` is a defined value: `freeze x` $\longrightarrow$ `x`

When `x` is a poison value: `freeze x` $\longrightarrow$ `0`, `1`, `2`, …

Nondet. Choice of
A Defined Value

Our Solution

Loop Unswitching

Our UB Model:

Branching on poison is

Undefined Behavior

0

```
while (n > 0) {
  if (cond)
    A
  else
    B
}
```

UB

poison

```
if (cond)
  while (n > 0)
  { A }
else
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Our Solution

Loop Unswitching

Our UB Model:

Branching on poison is

Undefined Behavior

0

```
while (n > 0) {
  if (cond)
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  else
    B
}
```

UB

poison

```
if (freeze(cond))
  while (n > 0)
  { A }
else
  while (n > 0)
  { B }
```

Our Solution
Loop Unswitching

Our UB Model:
Branching on poison is
Undefined Behavior

0

```
while (n > 0) {
  if (cond)
    A
  else
    B
}
```

UB true false poison

```
if (freeze(cond))
  while (n > 0)
  { A }
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  { B }
```

Our Solution

Loop Unswitching

Our UB Model:
Branching on poison is
Undefined Behavior

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```
while (n > 0) {
  if (cond)
    A
  else
    B
}
```

true false poison

```
if (freeze(cond))
  while (n > 0)
  { A }
else
  while (n > 0)
  { B }
```

Summary of Freeze

Compilers can control poison!

- Branching on freeze(poison)   =>   Nondet.
  - Used for Loop Unswitching
- Branching on poison   =>   UB
  - Used for Global Value Numbering

Summary of Freeze

Compilers can control poison!

- Branching on freeze(poison) => Nondet.
  - Used for Loop Unswitching
- Branching on poison => UB
  - Used for Global Value Numbering

Freeze can also fix many other UB-related problems.

Further Example

Hoisting Division

```
// bitwise-or
k = x | 0x1

while (n > 0)
  use(100 / k)
```

```
// bitwise-or
k = x | 0x1
t = 100 / k
while (n > 0)
  use(t)
```

Further Example

Hoisting Division

poison

```
k = x | 0x1
```

0

```
while (n > 0)
  use(100 / k)
```

poison

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k = x | 0x1
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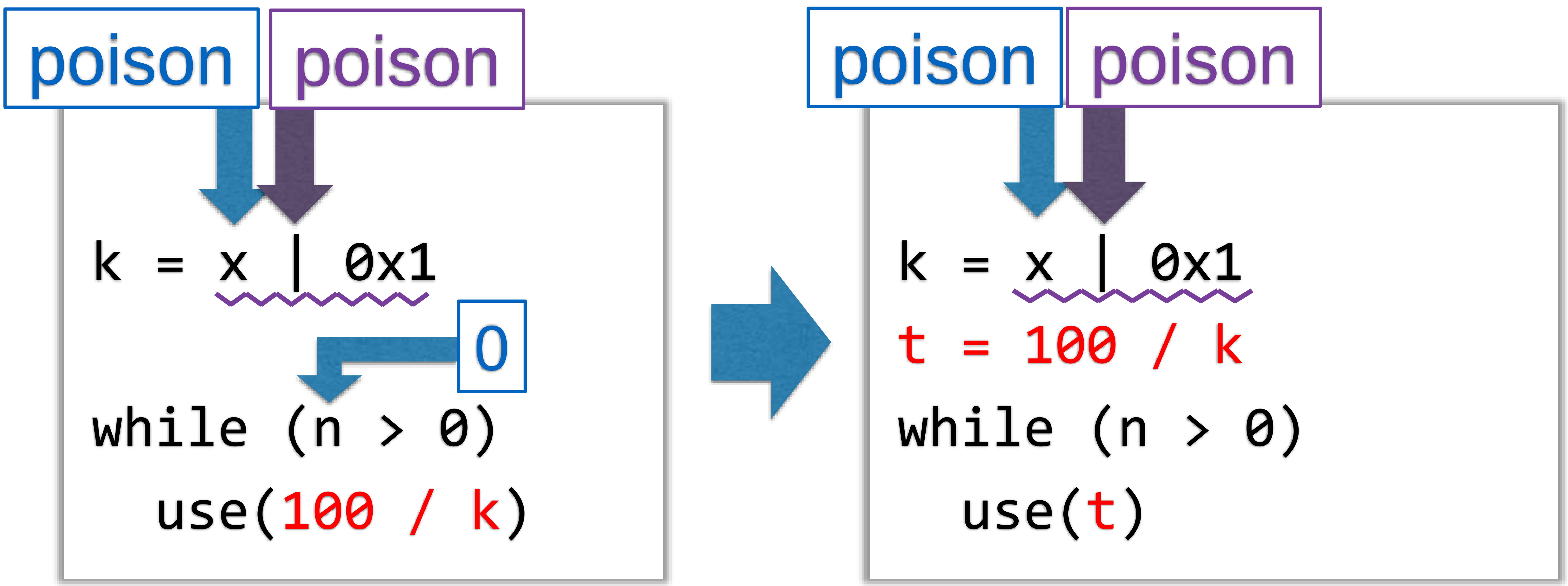
Hoisting Division



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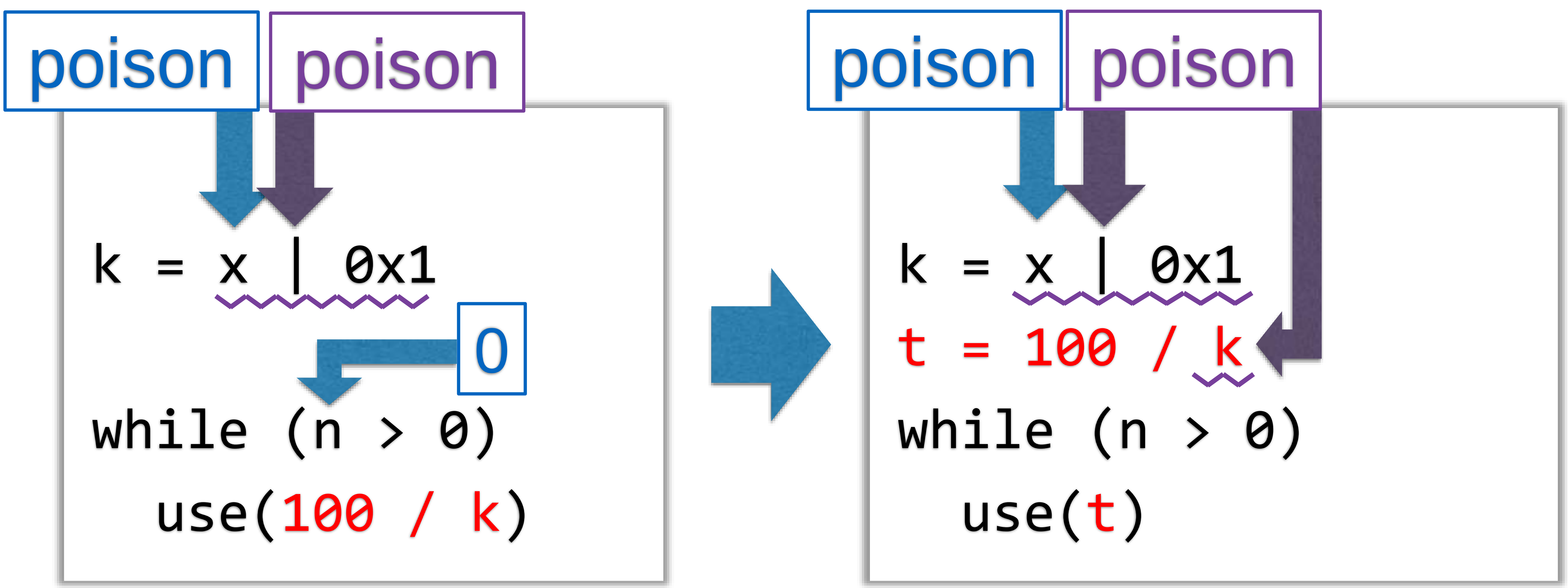

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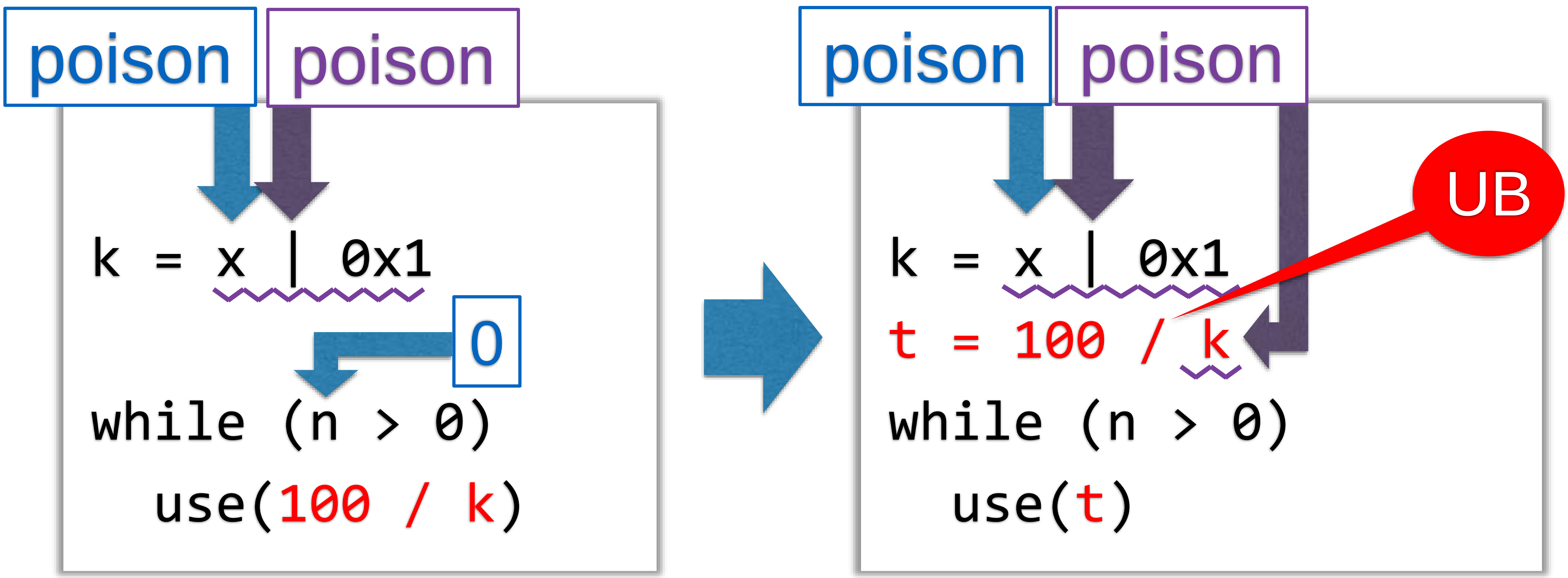
Hoisting Division



Further Example

Hoisting Division

LLVM does not currently support it.

poison poison

```
k = x | 0x1
while (n > 0)
  use(100 / k)
```

0

poison poison

UB

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Further Example

Hoisting Division

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k = freeze(x) | 0x1
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Further Example

Hoisting Division

LLVM does not currently support it.

poison

poison

```
k = x | 0x1
```

0

```
while (n > 0)
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A defined value

poison

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```

Further Example

Hoisting Division

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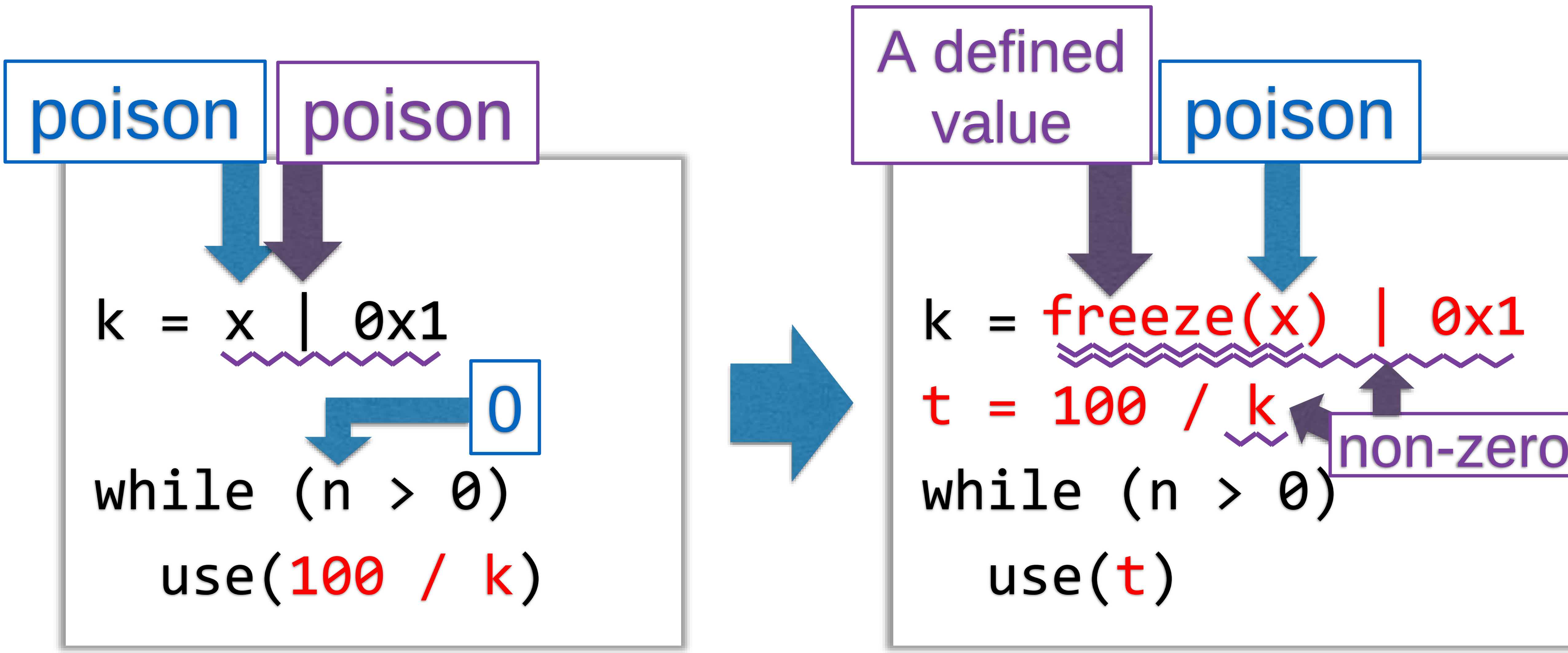

Further Example

Hoisting Division

Freeze can make LLVM support it!

poison poison

```
k = x | 0x1
while (n > 0)
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```

0

A defined value

poison

```
k = freeze(x) | 0x1
t = 100 / k
while (n > 0)
  use(t)
```

non-zero

Implementation

- Target: LLVM 4.0 RC 4 (Mar. 2017)
- Add Freeze instruction to LLVM IR
- Bug Fixes Using Freeze
  - Loop Unswitching Optimization
  - C Bitfield Translation to LLVM IR
  - InstCombine Optimizations

* More details are given in the paper

Experiment Results

- Benchmarks (4.6M LOC):
  - SPEC CPU2006
  - LLVM Nightly Test
  - Large Single File Benchmarks
- Compilation Time: ± 1%
- Compilation Memory Usage: Max + 2%
- Generated Code Size: ± 0.5%
- Execution Time: ± 3%

* More details are given in the paper

"Freeze" Can Fix UB Semantics Without Significant Performance Penalty

- Benchmarks (4.6M LOC):
  - SPEC CPU2006
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- Compilation Time: $\pm$ 1%
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* More details are given in the paper

Conclusion

- Modern compilers' UB models cannot support some textbook optimizations.
- We propose "freeze" to fix such problems.
- Freeze has little impact on performance.