Dagstuhl Seminar on
Secure Compilation

Taming Undefined Behavior in LLVM

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Azul Systems

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Microsoft Research

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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

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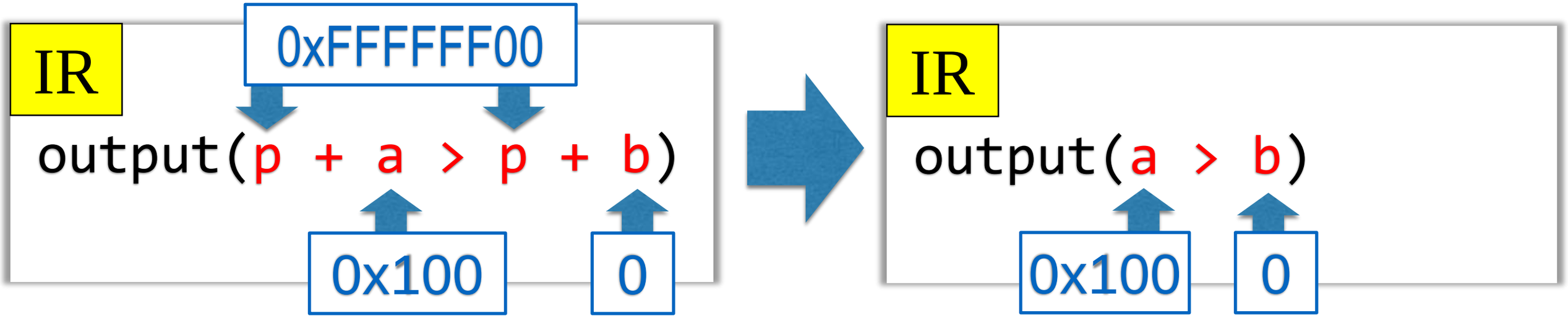

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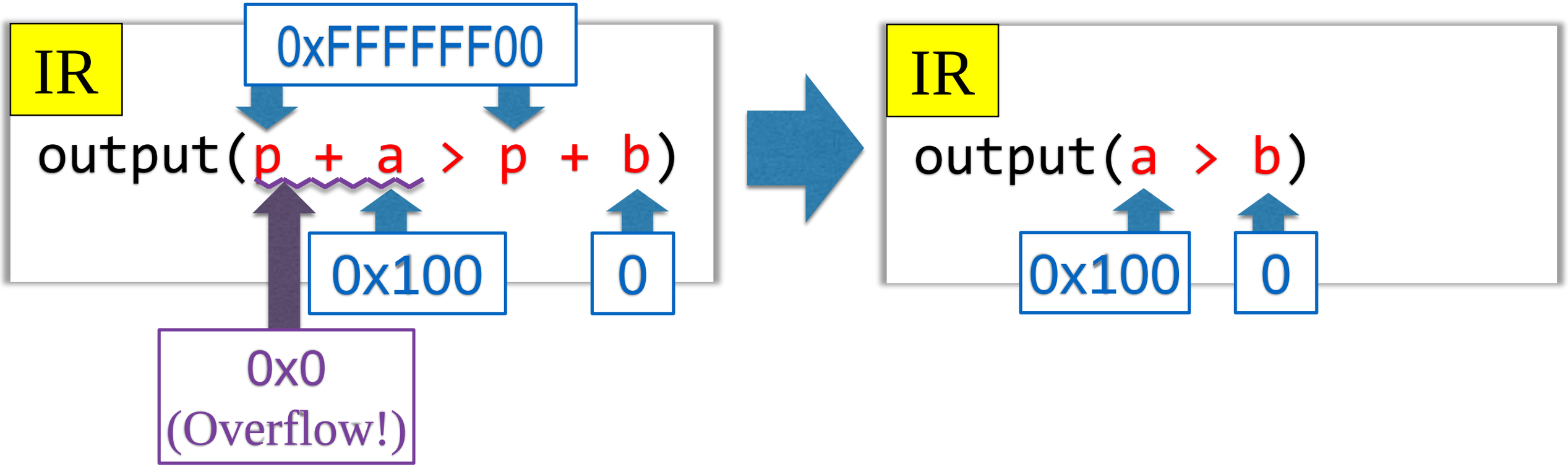

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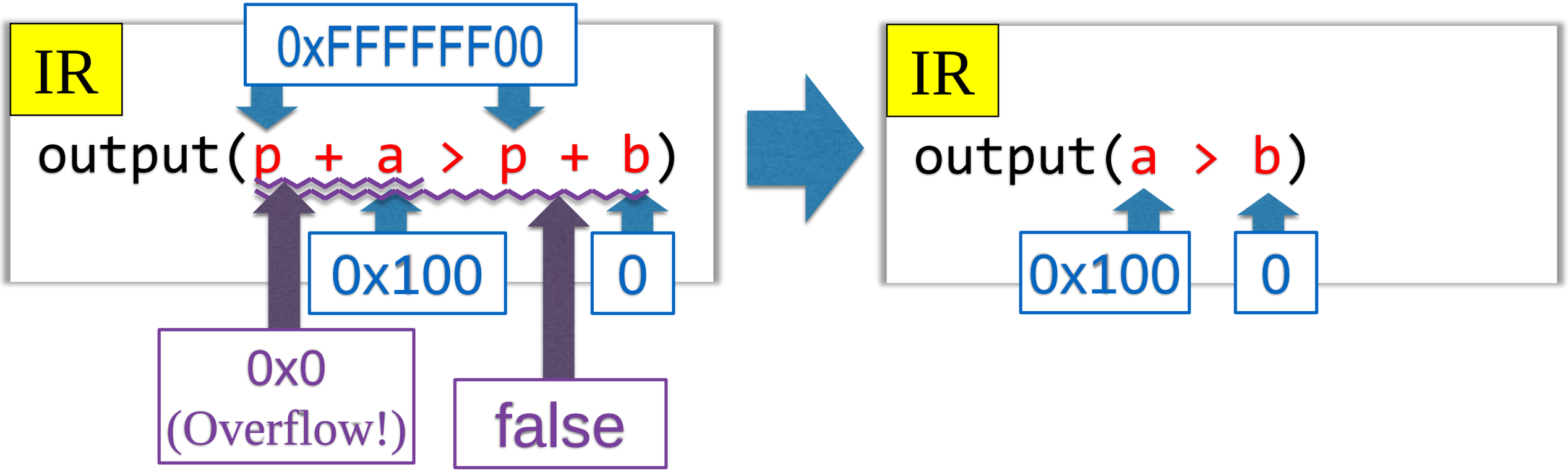

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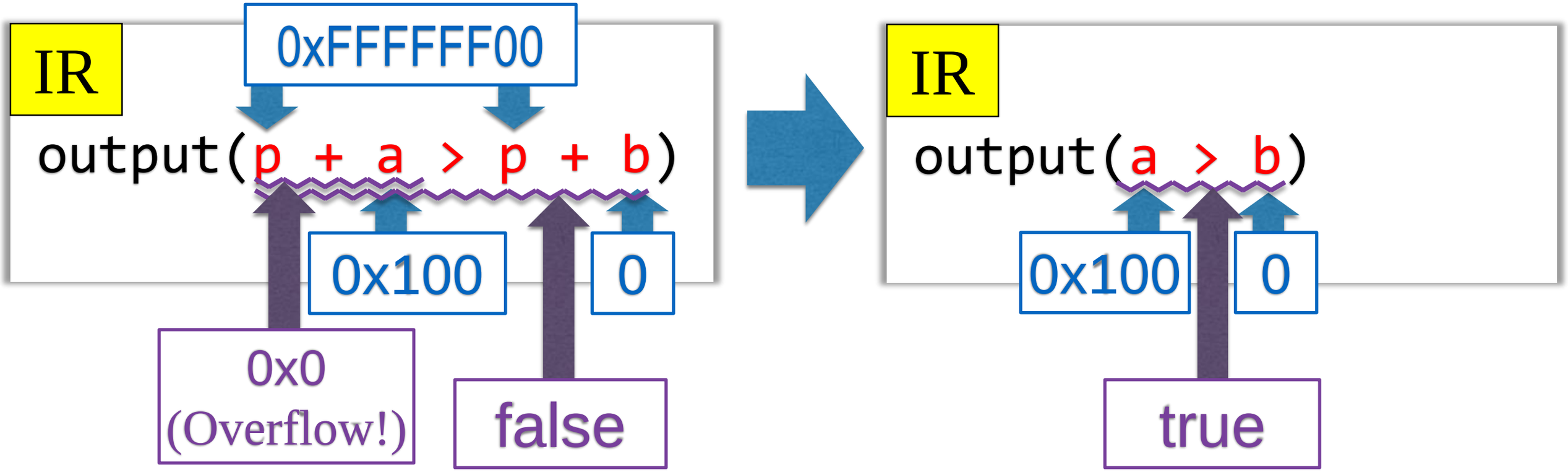

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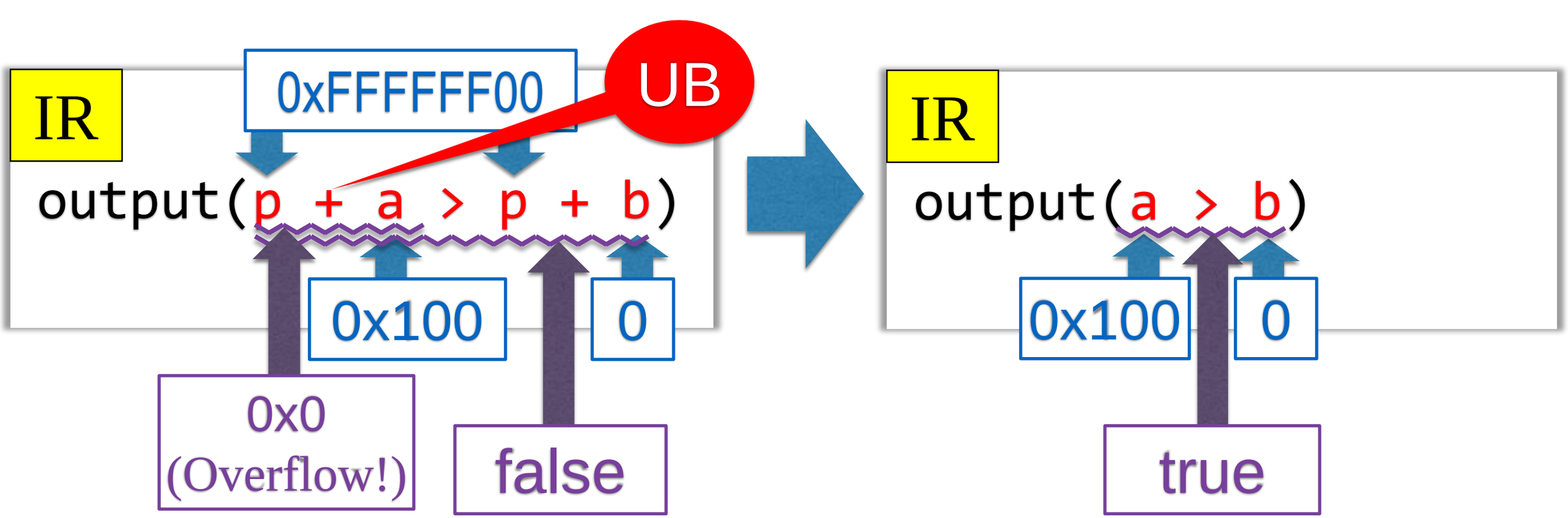
Peephole Optimization

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

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0xFFFFFF00

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0

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q = p + 0x100
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}
```

0xFFFFFF00

Overflow!

0

Problems with UB

Loop Invariant Code Motion

Simple UB Model:

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IR

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

0

0xFFFFFF00

0xFFFFFF00

Overflow!

UB

IR

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

0

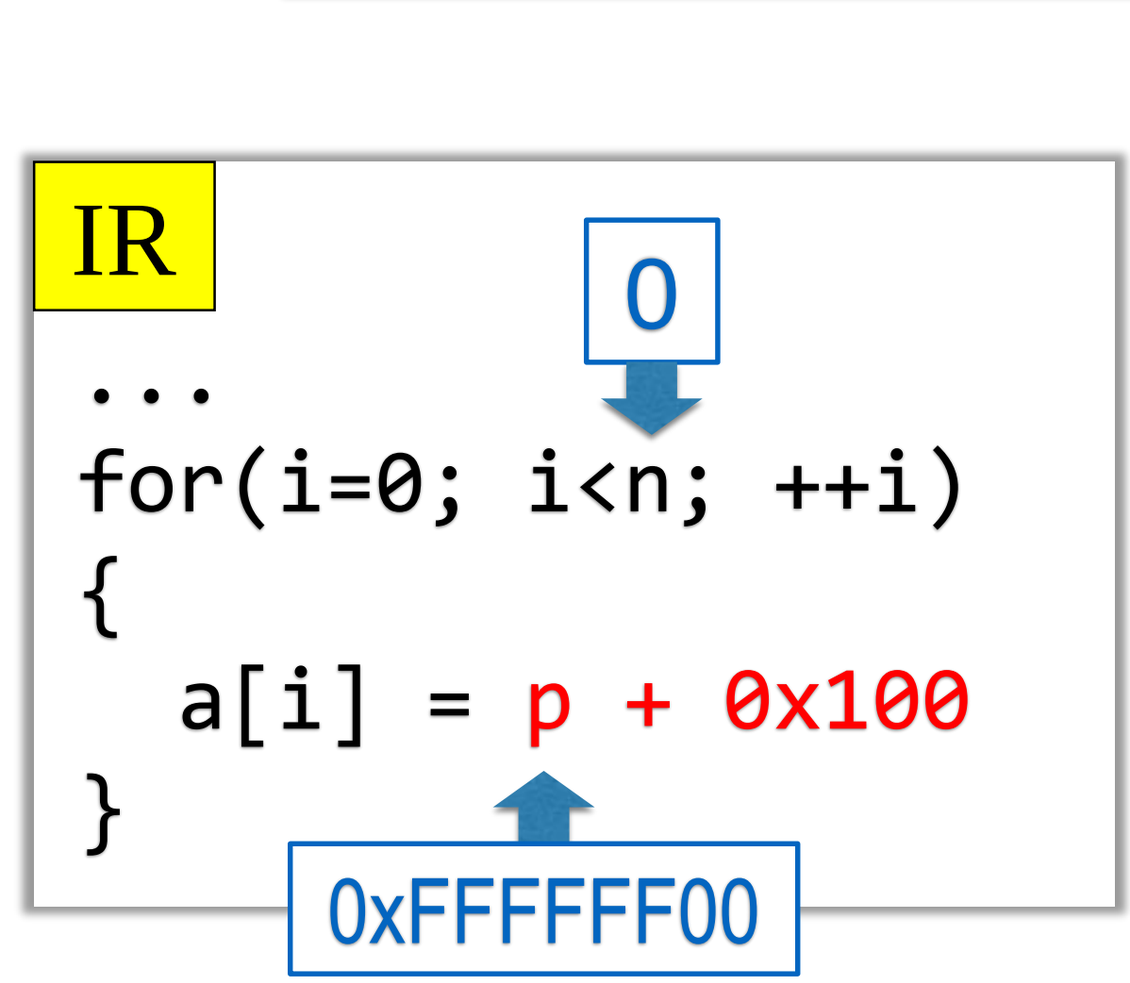
Existing Approaches

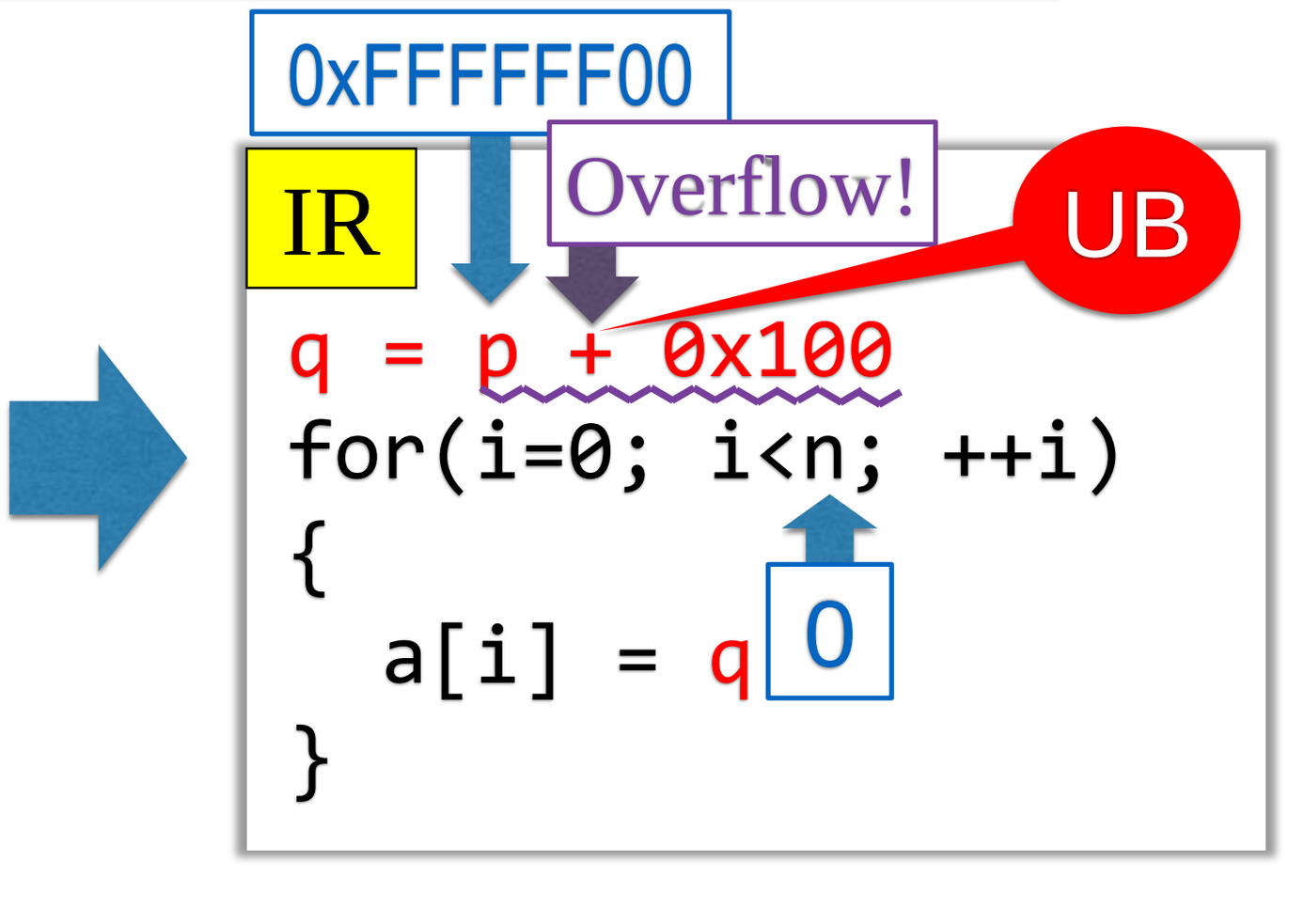
Poison Value: A Deferred UB

Simple UB Model:

Pointer Arithmetic Overflow is

Undefined Behavior



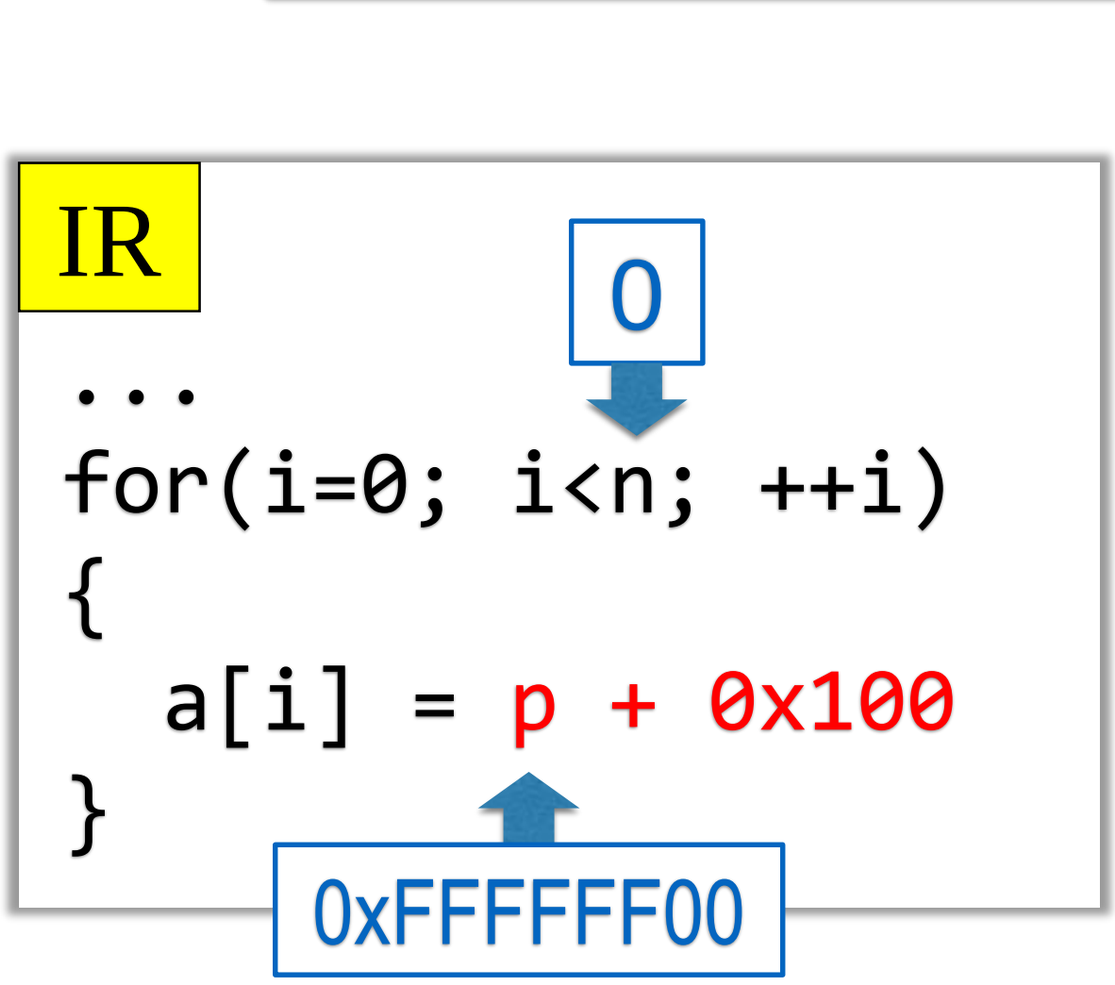


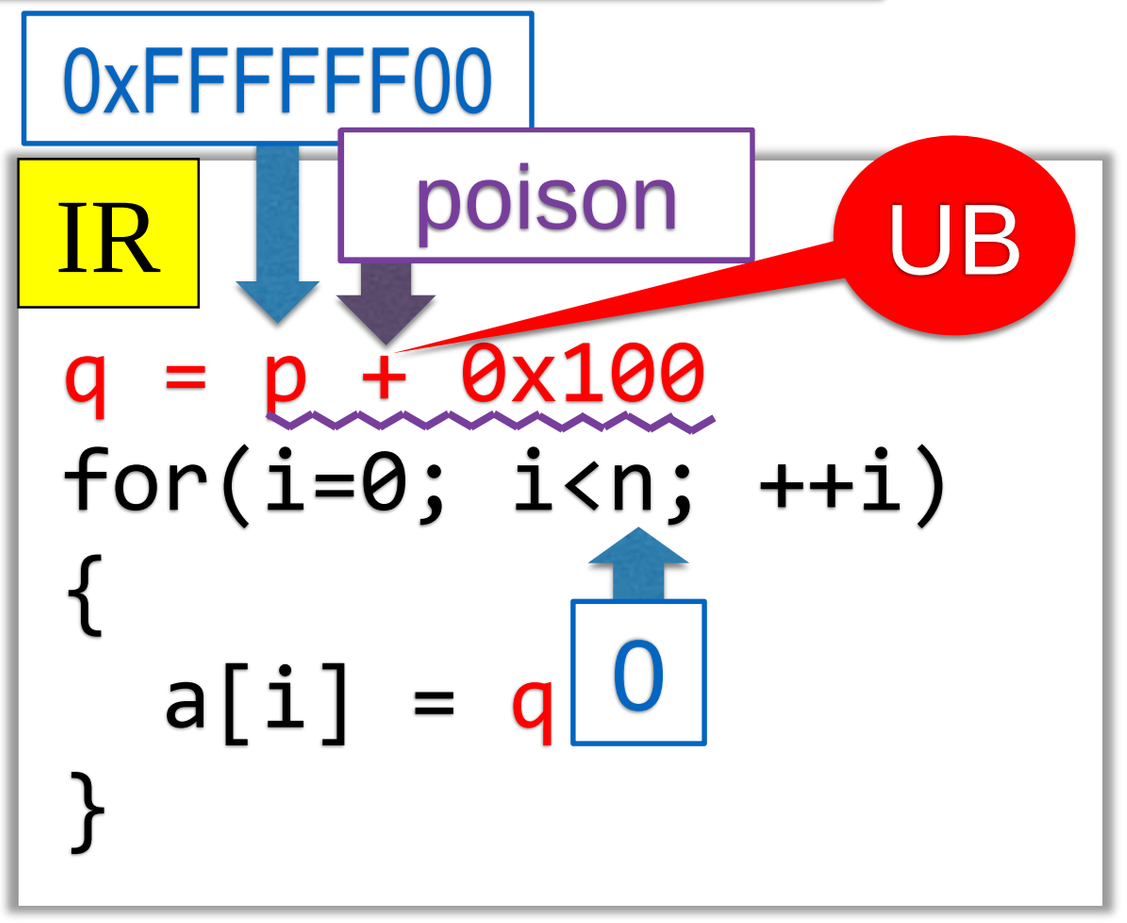
Poison Value: A Deferred UB

LLVM's UB Model:

Pointer Arithmetic Overflow is

A Poison "Value"





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...
for(i=0; i<n; ++i)
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0

0xFFFFFF00

IR

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

0xFFFFFF00

poison

0

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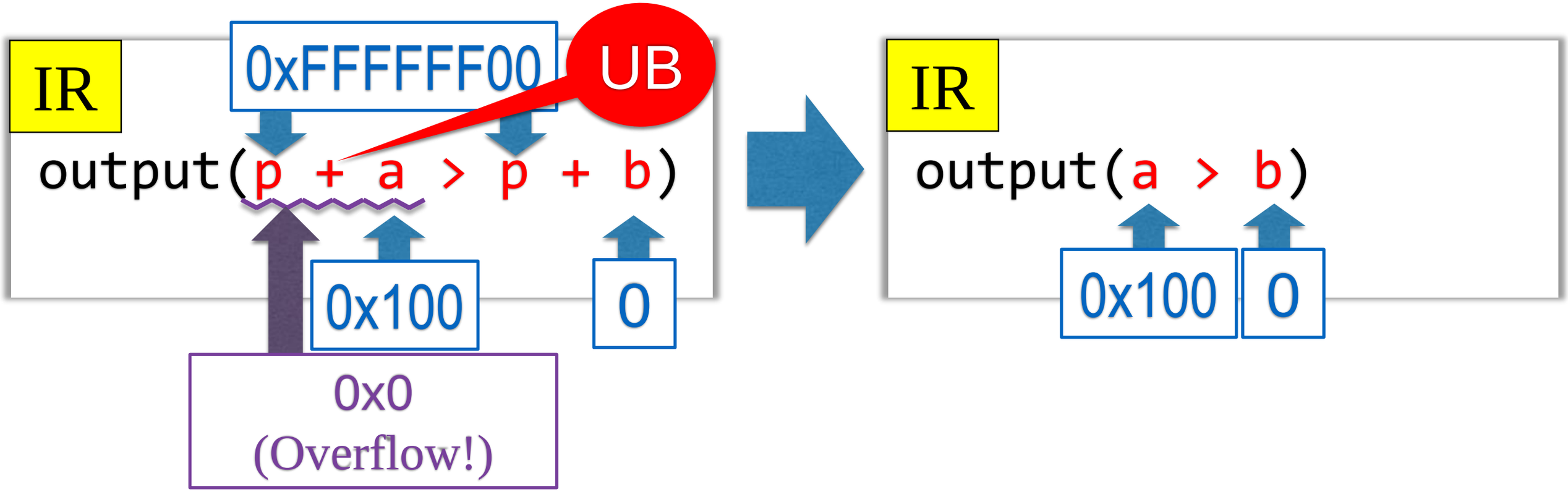

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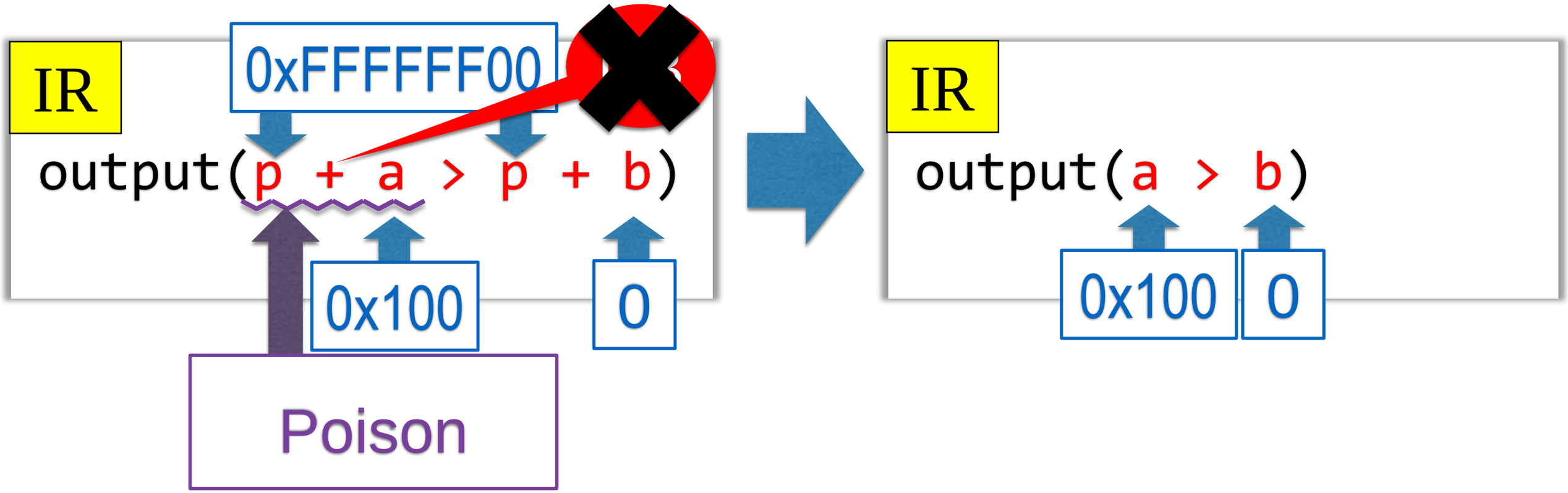

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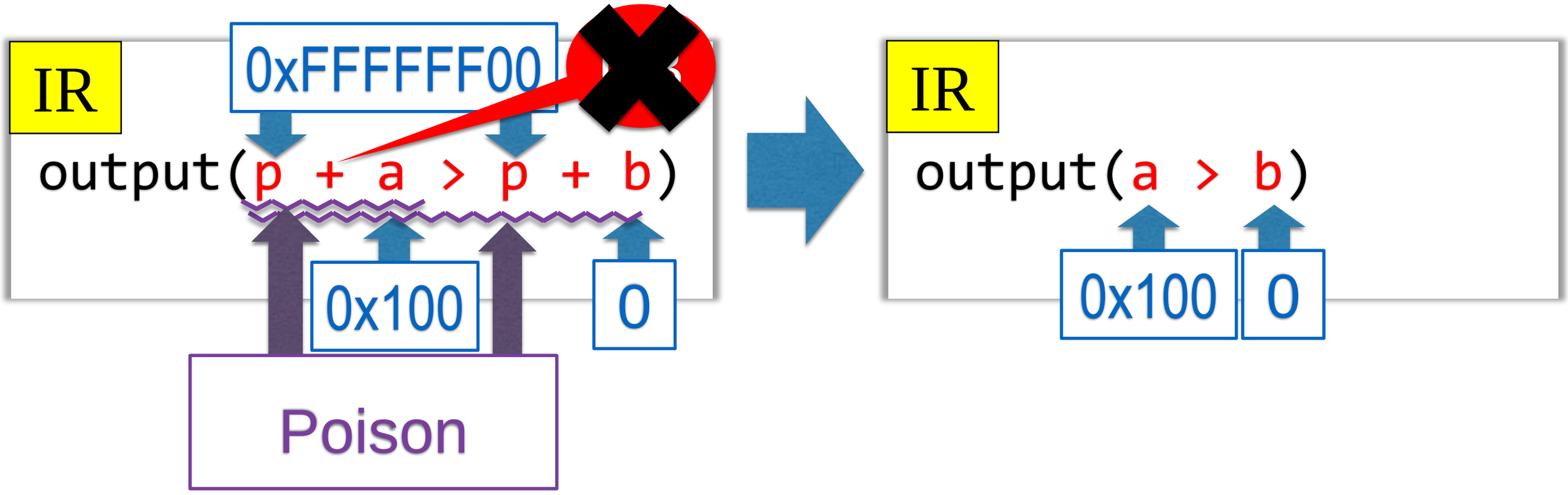

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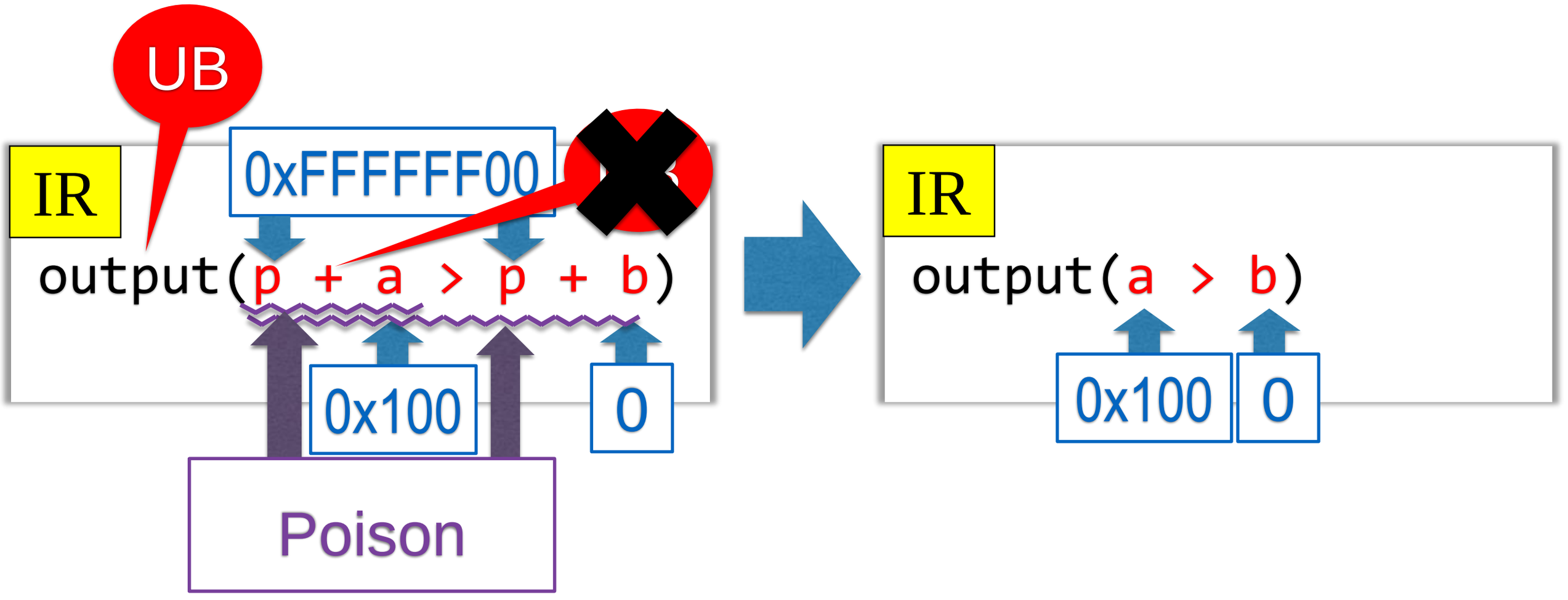

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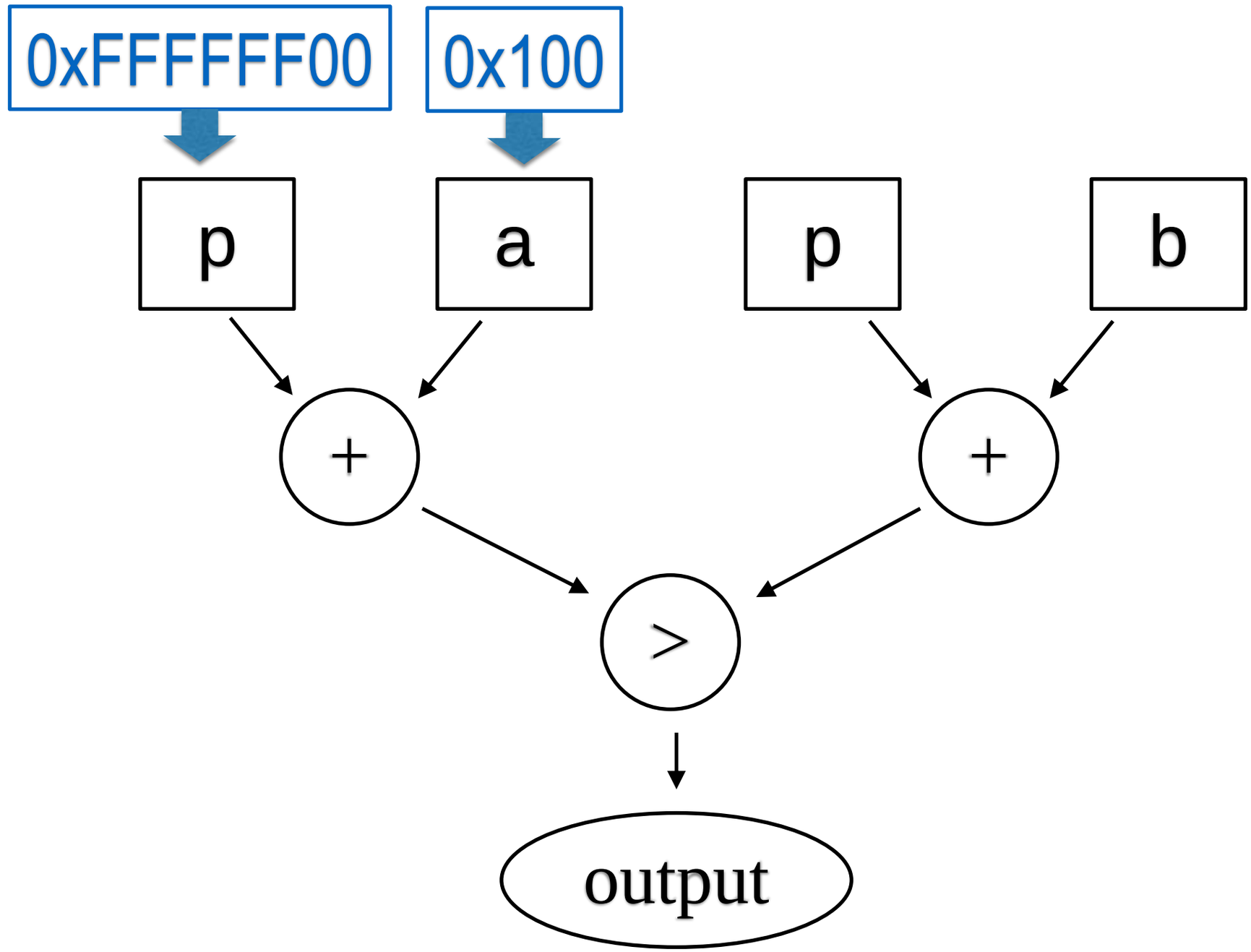

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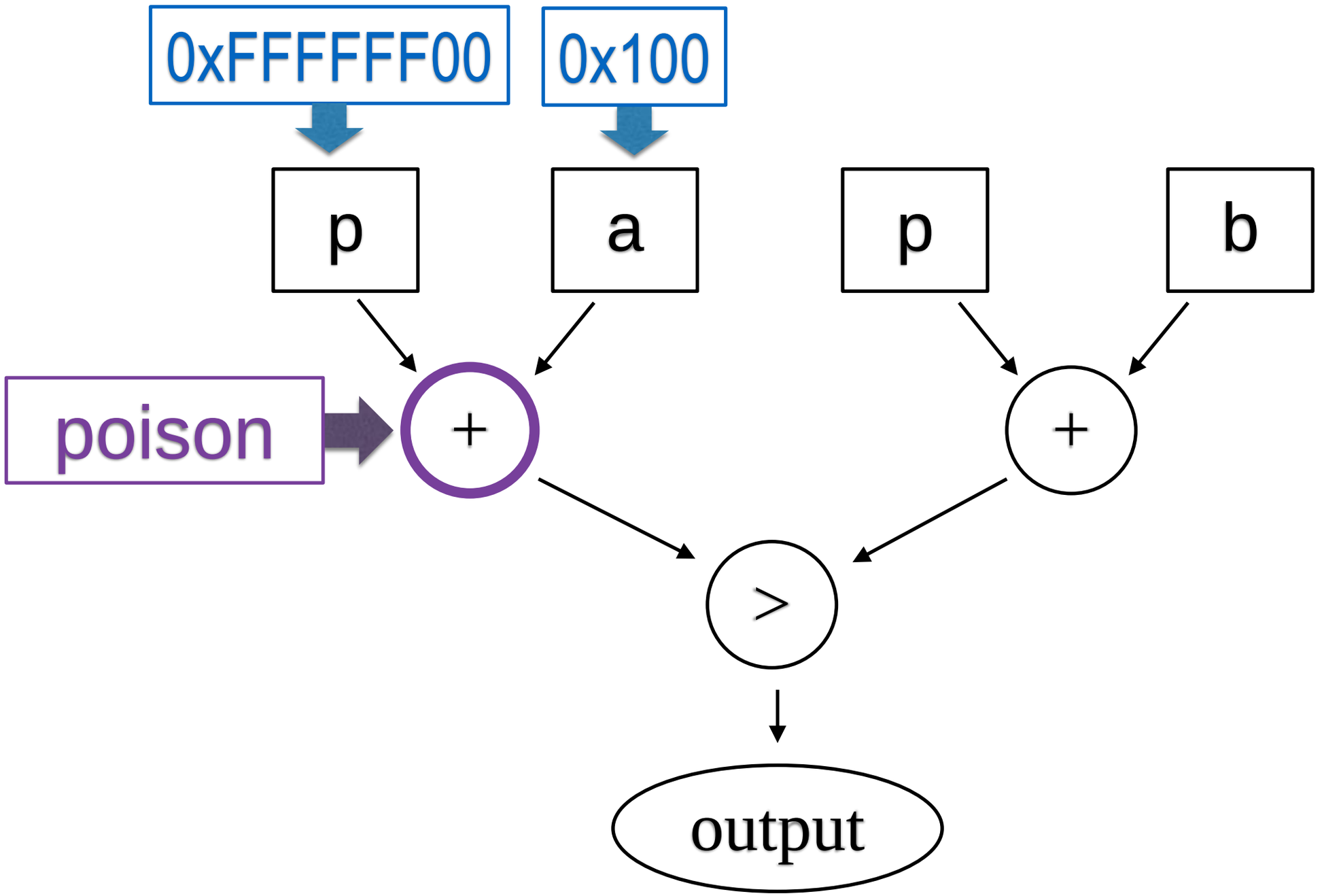

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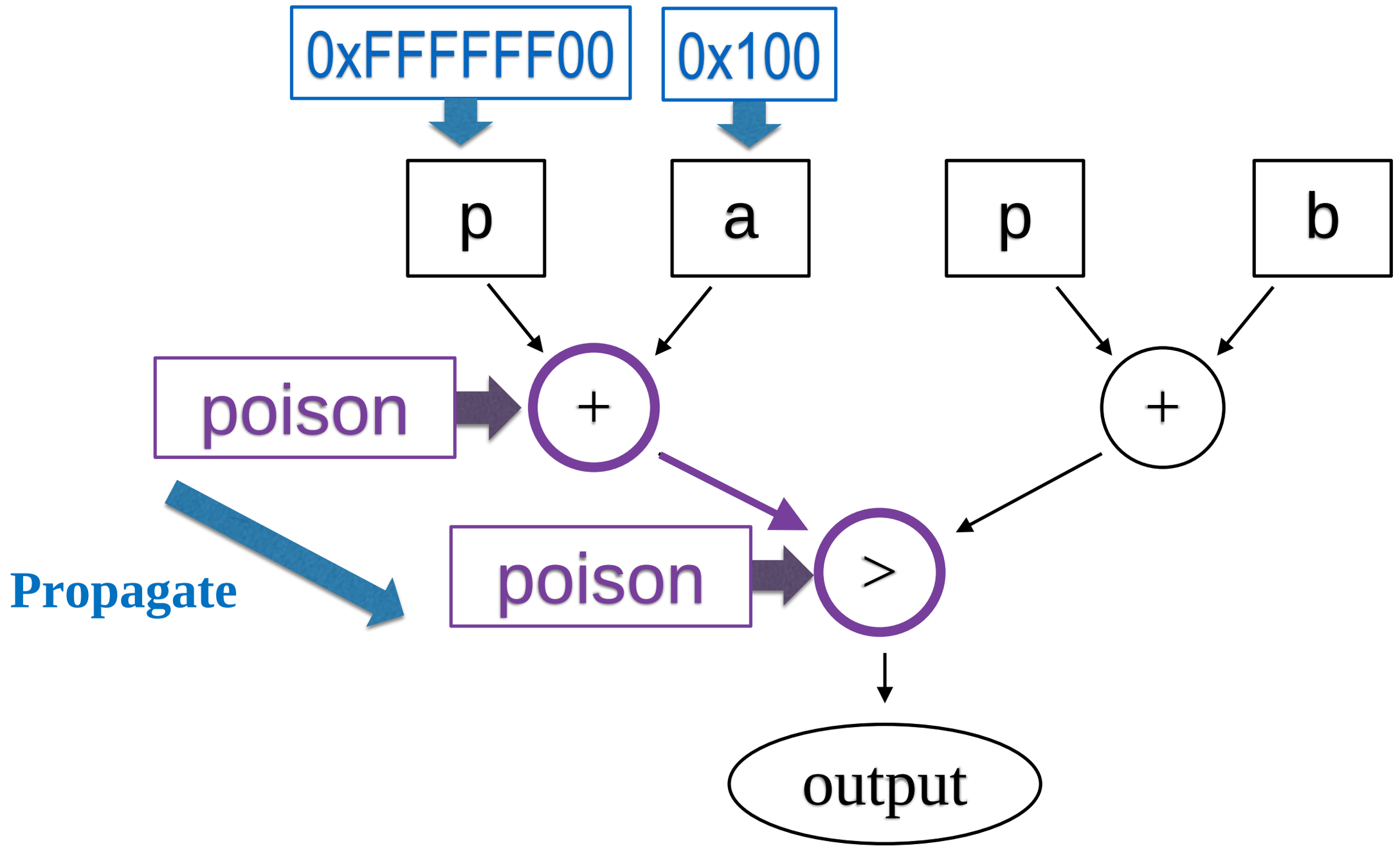

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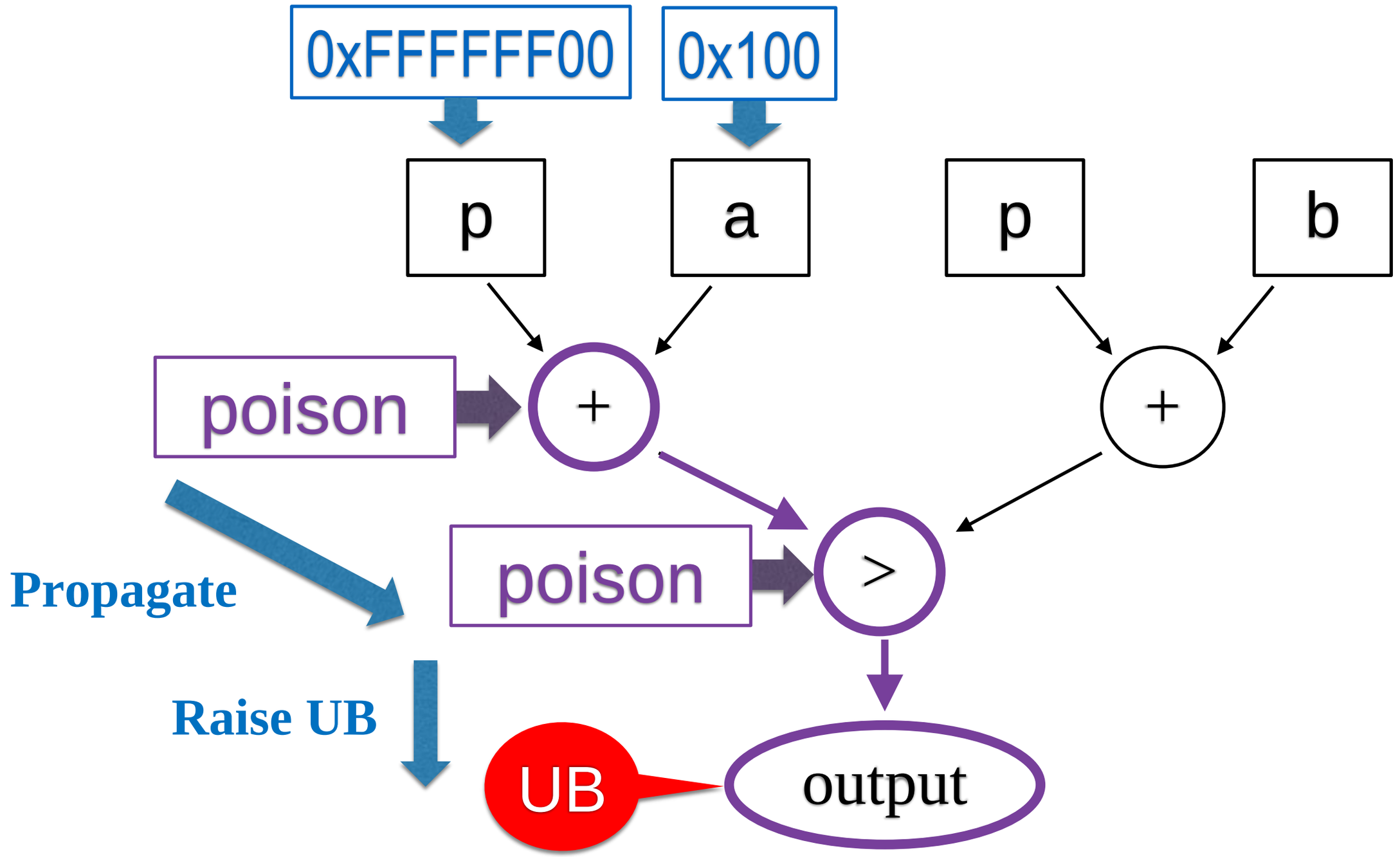

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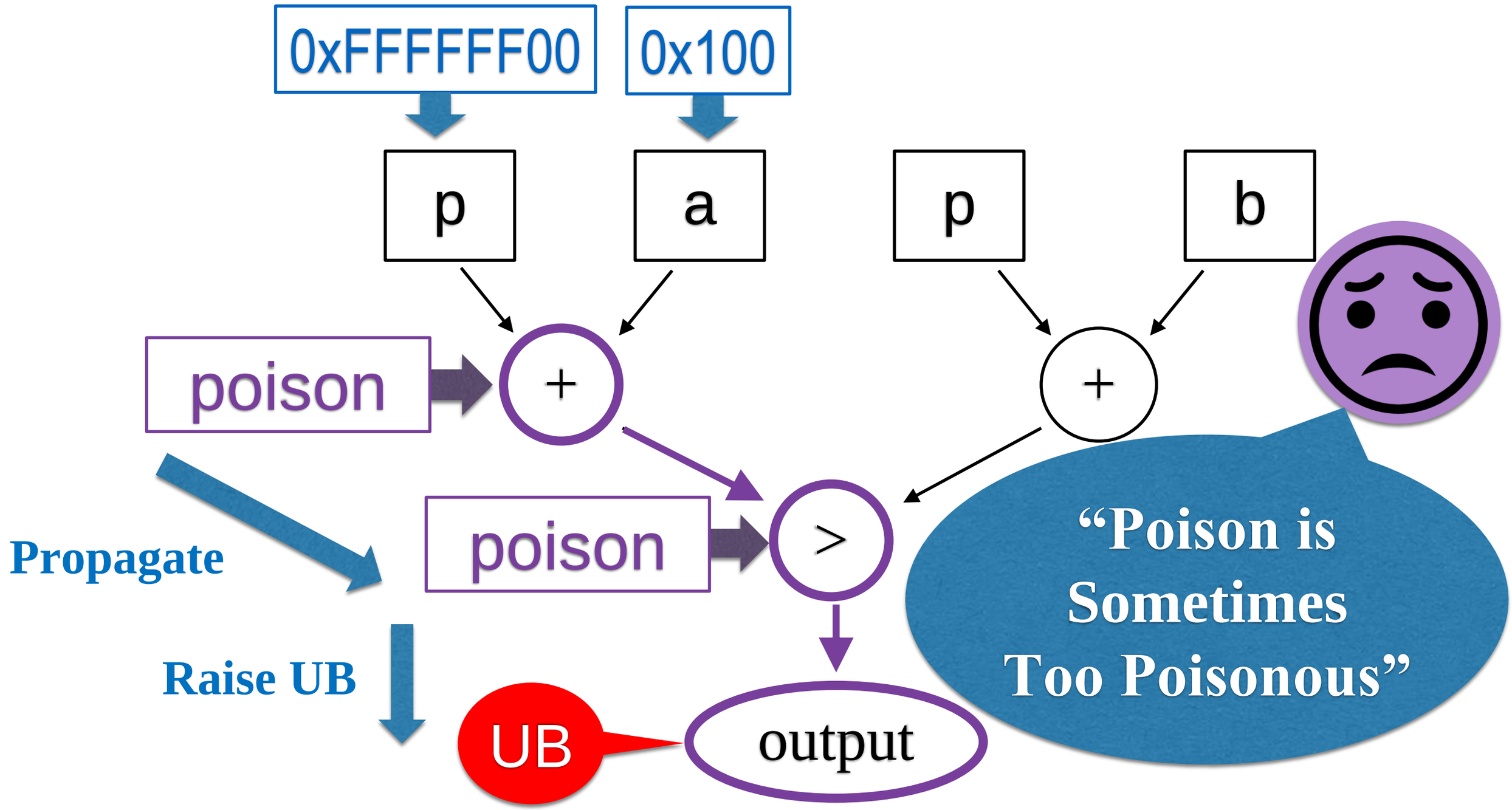

Problem

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) {

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}
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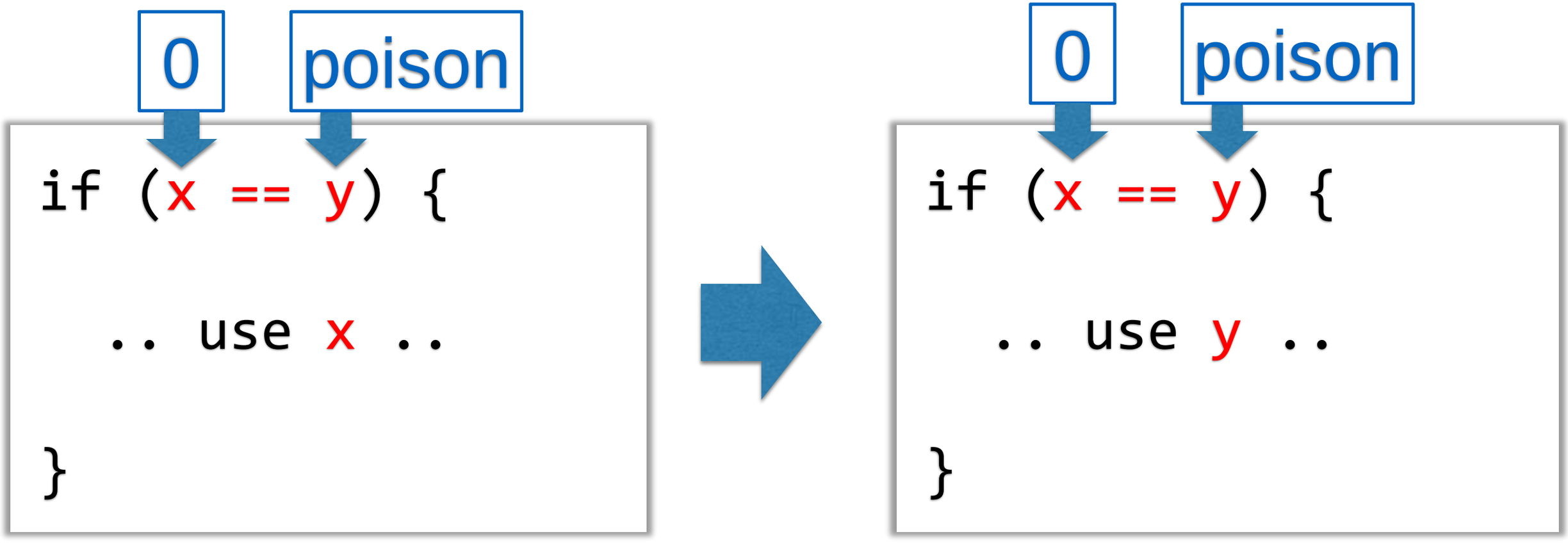

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???

poison

0 poison

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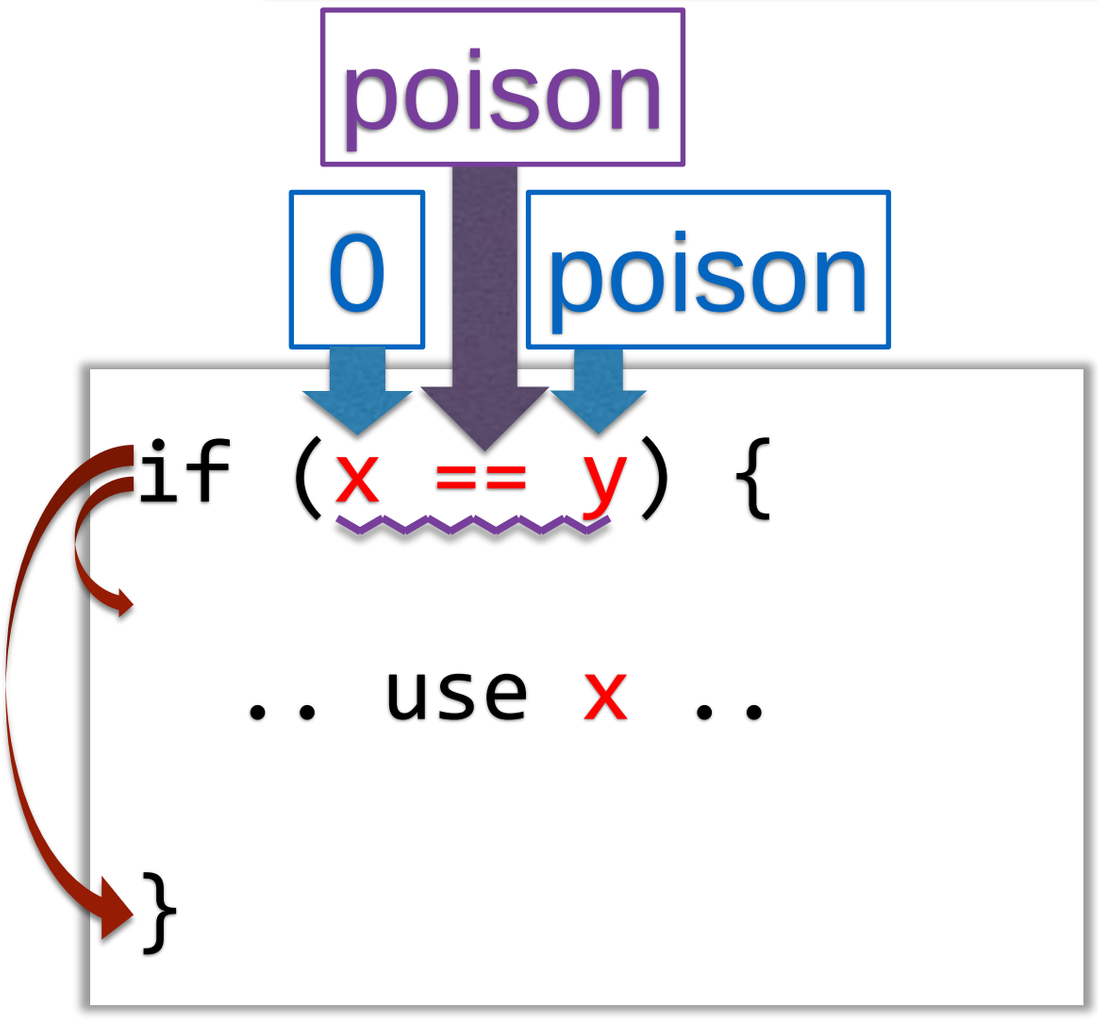

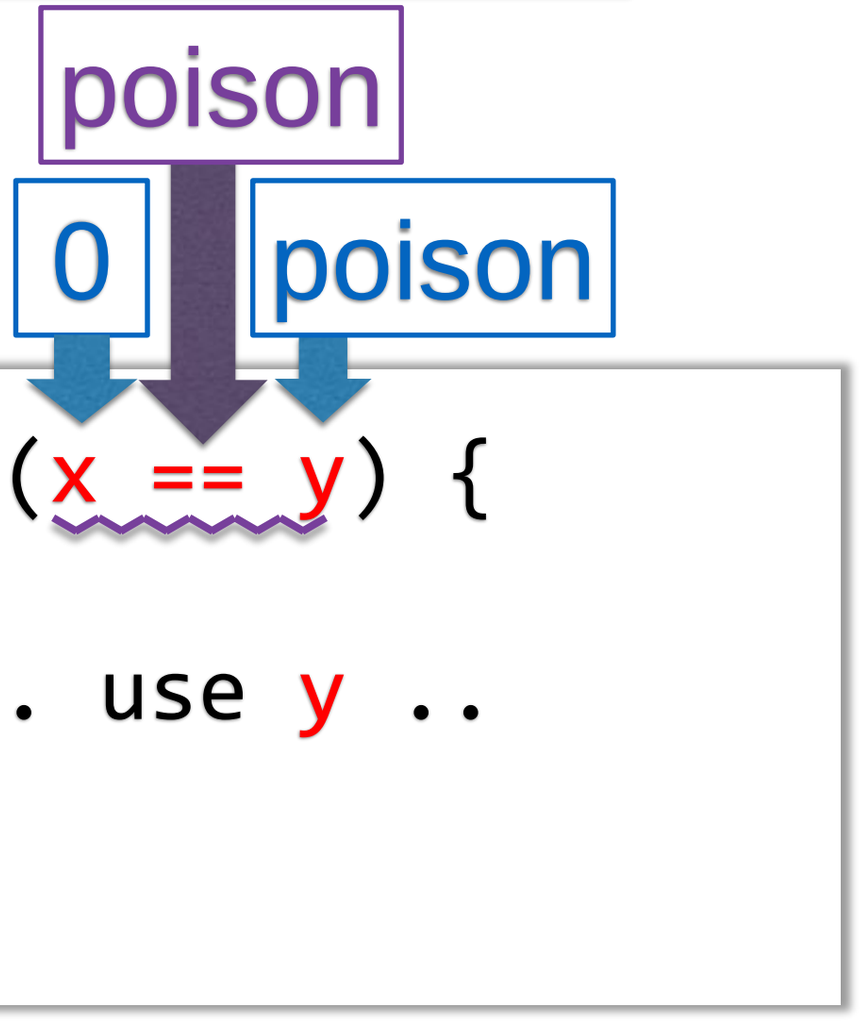

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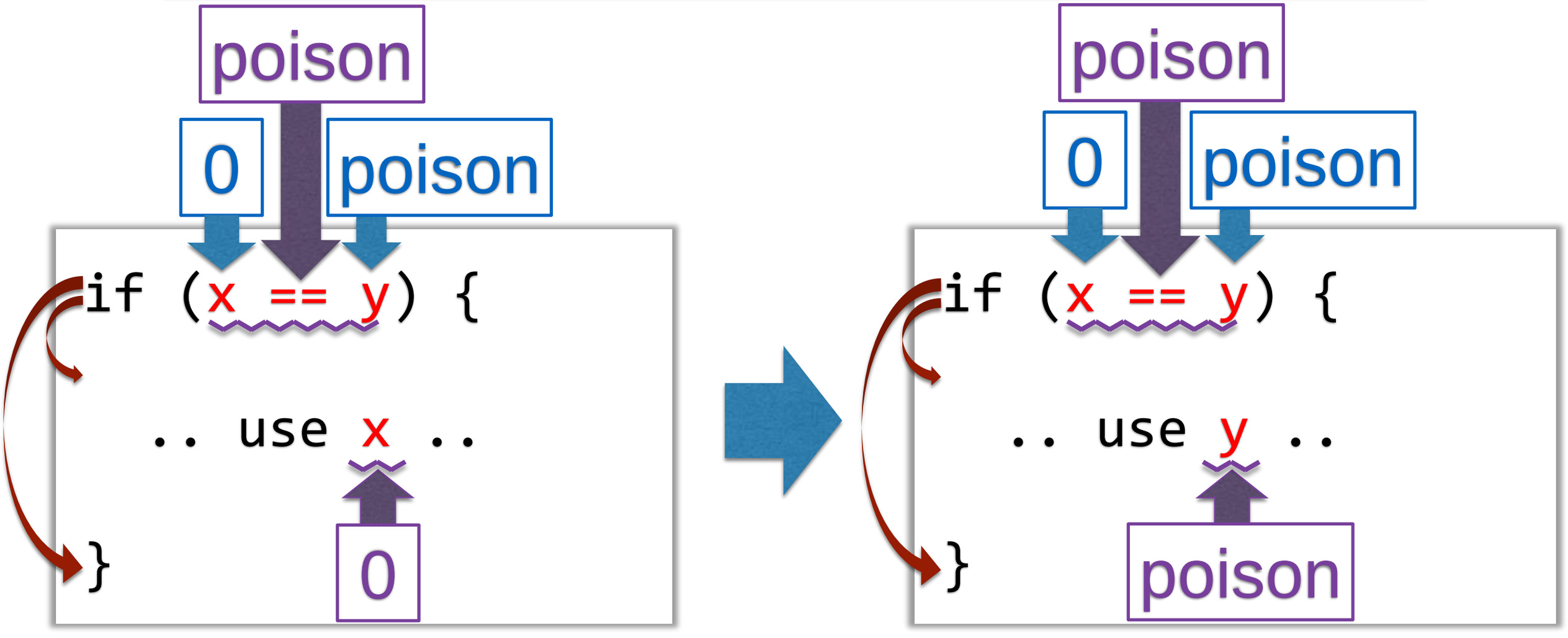

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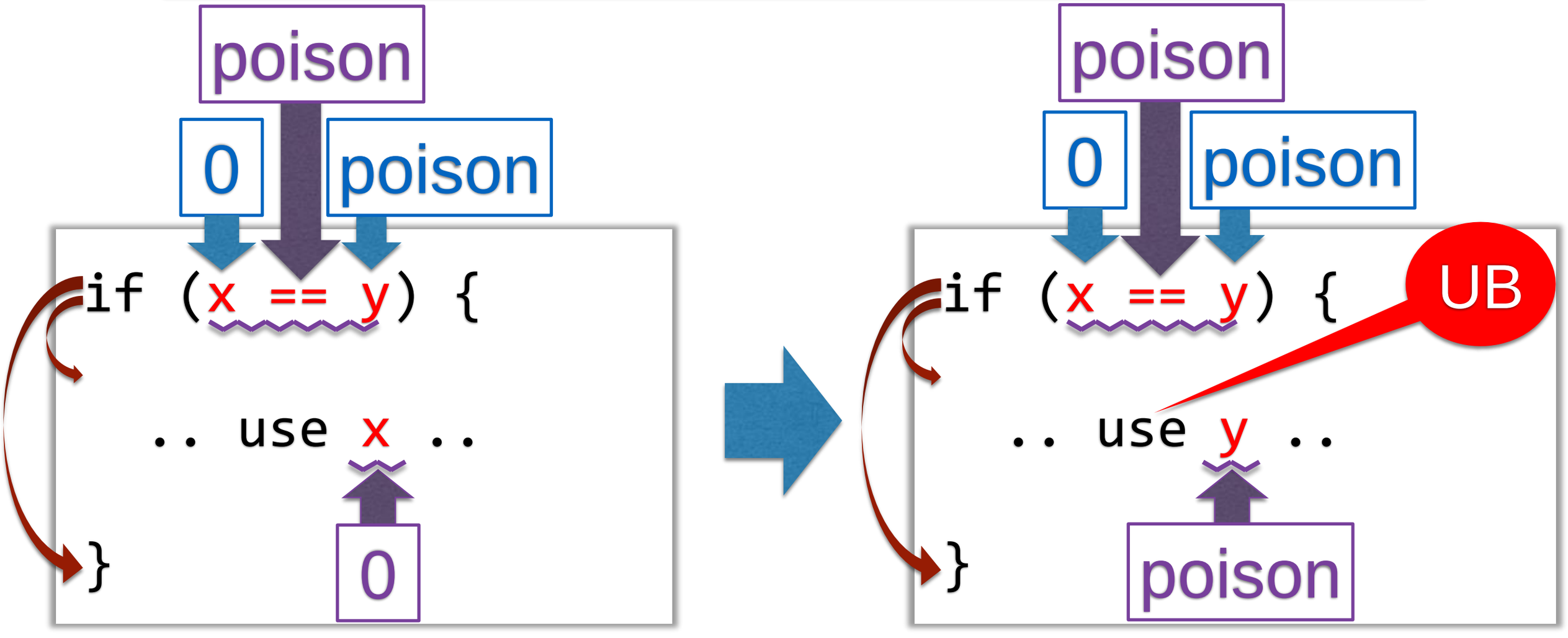

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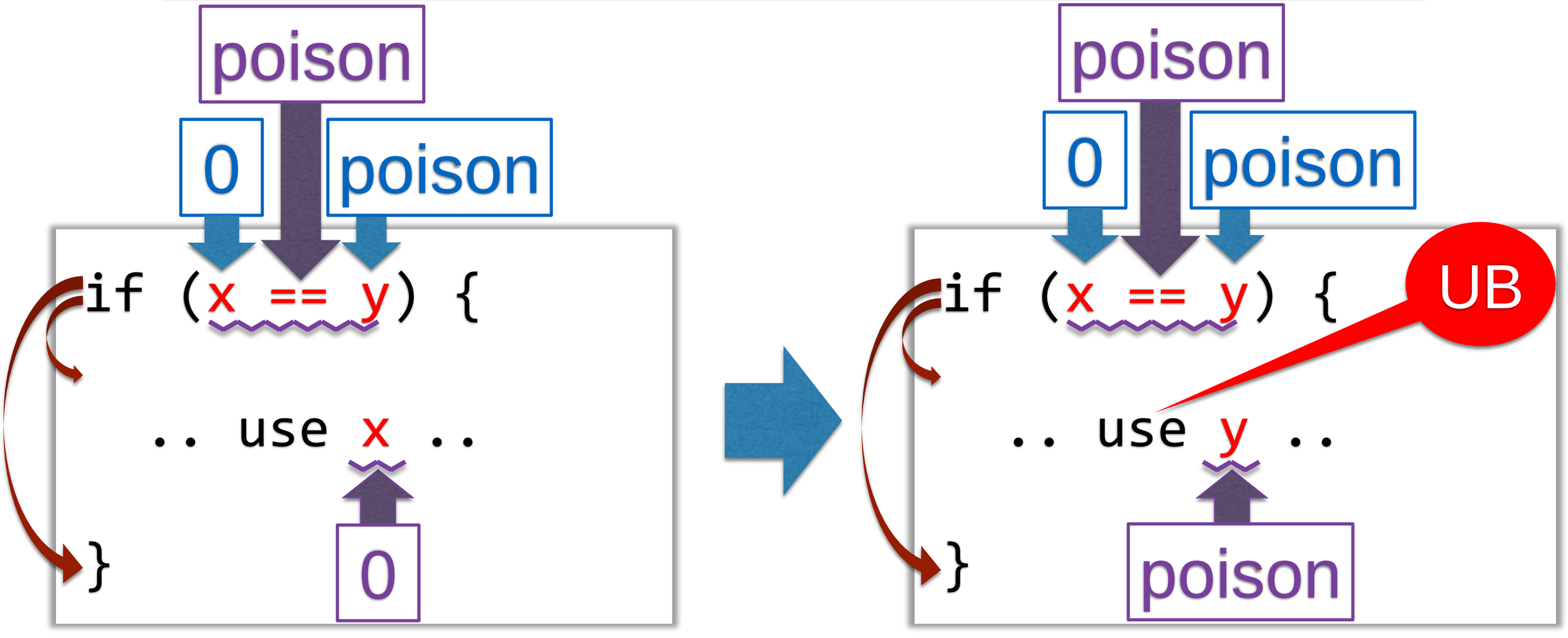
Global Value Numbering (GVN)

LLVM's UB Model:

Branching on poison is

Undefined Behavior



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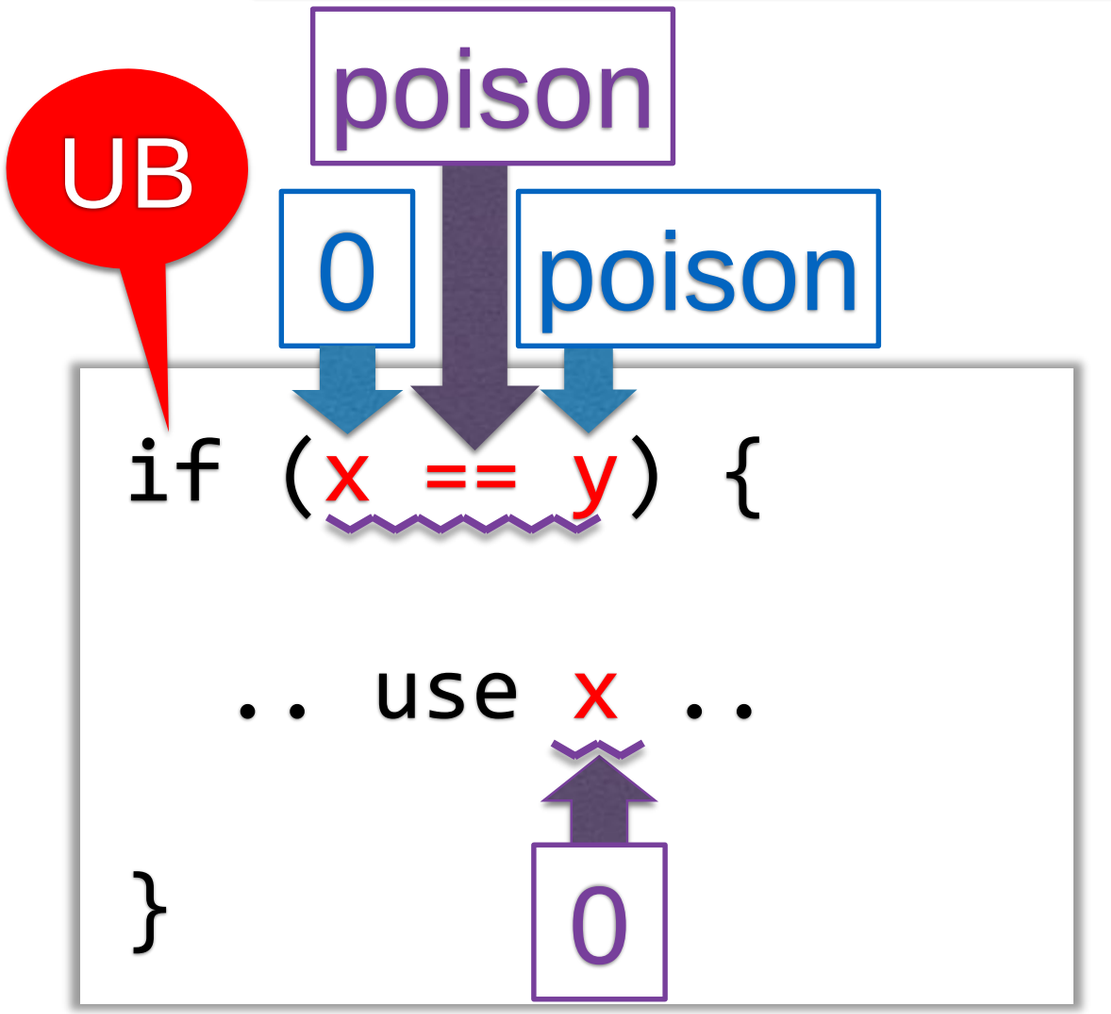

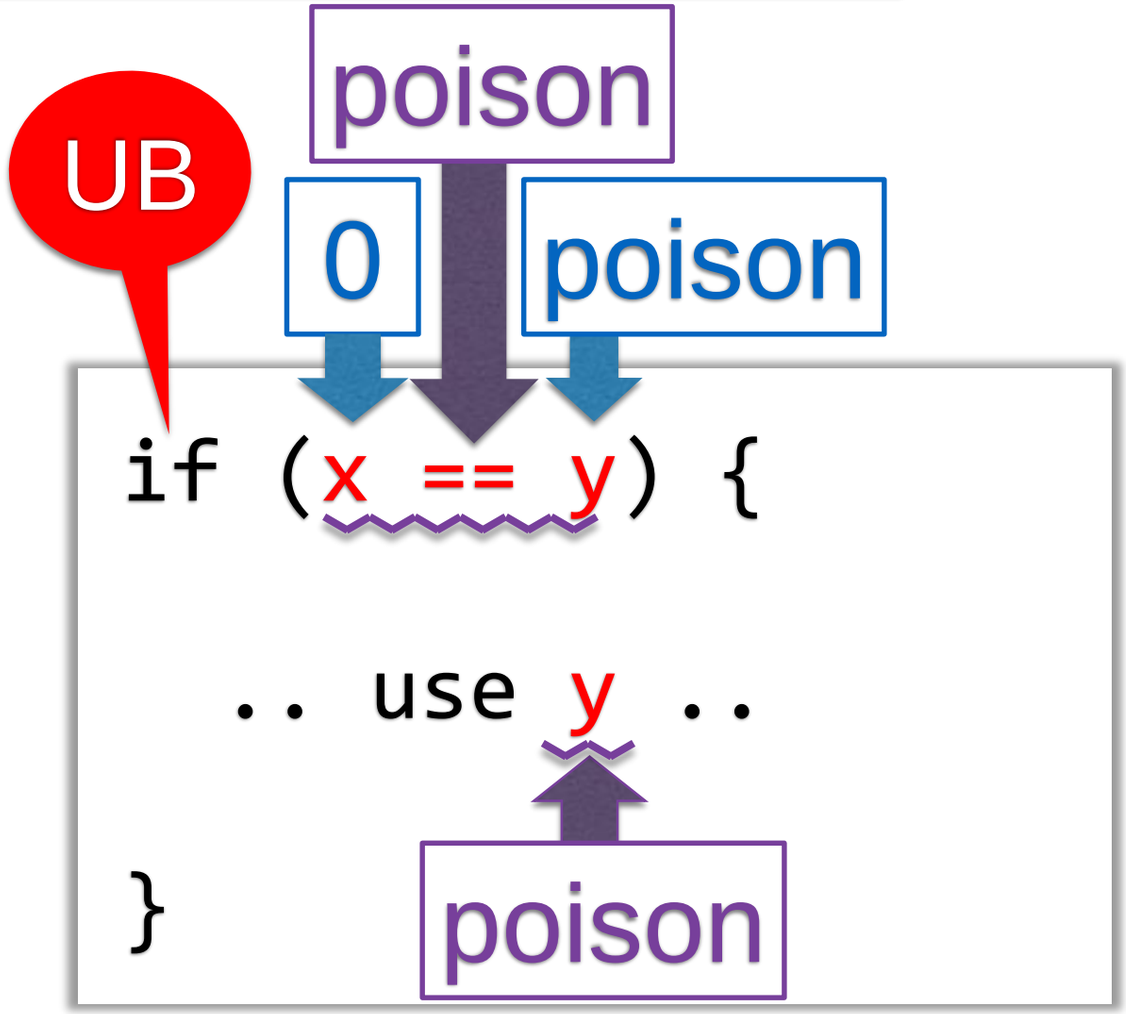

Problems with LLVM's UB

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

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

poison

poison

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

0

Problems with LLVM's UB

Loop Unswitching (LU)

LLVM's UB Model:

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```
while (n > 0) {
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}
```

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.
  - https://bugs.llvm.org/show_bug.cgi?id=31652
  - It is being discussed in the community
  - No solution has been found yet
- 6 months later, LLVM miscompiles itself due to it.
  - https://bugs.llvm.org/show_bug.cgi?id=33652
  - http://lists.llvm.org/pipermail/llvm-dev/2017-July/thread.html#115497

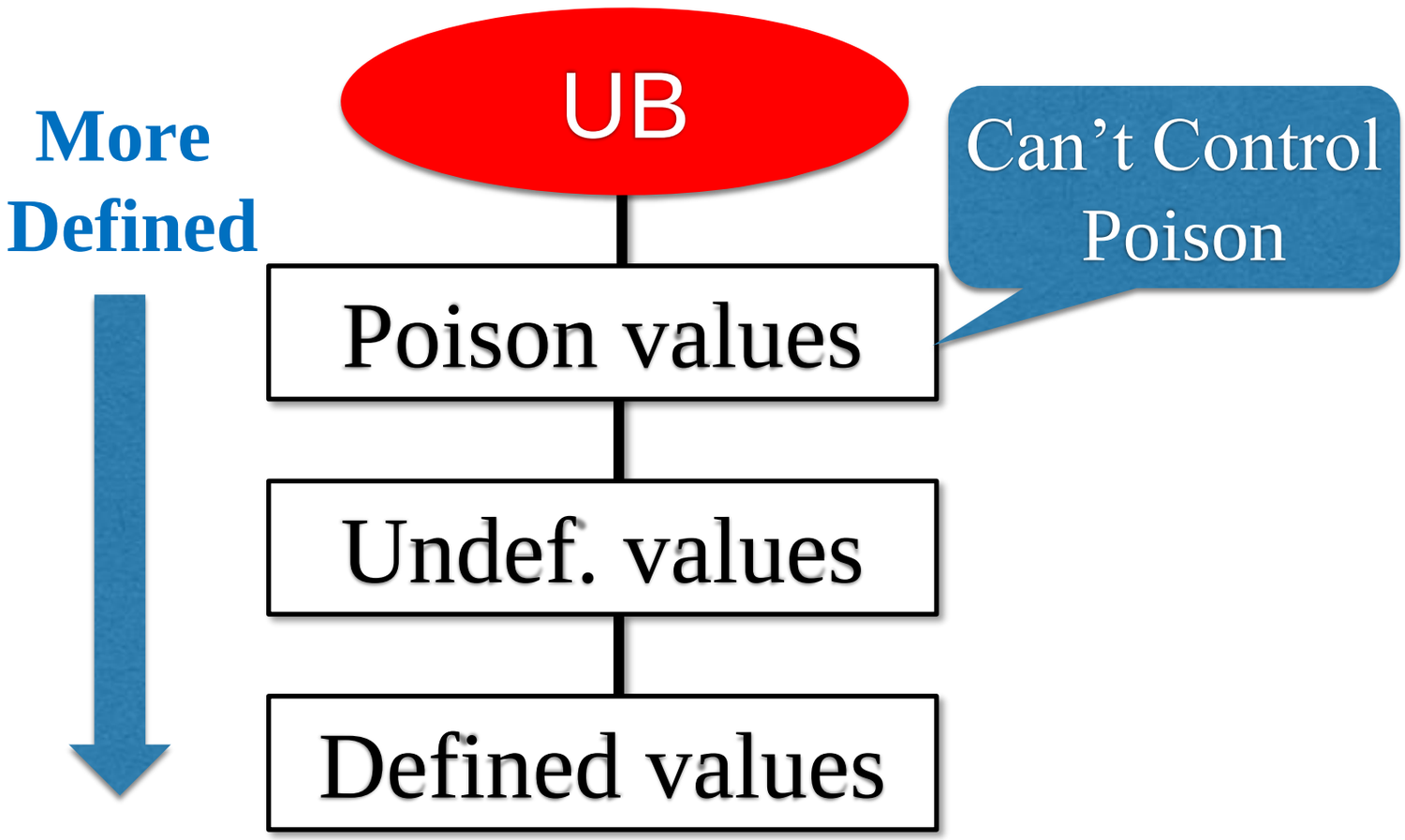
Our Proposal

Overview

Existing Approaches

Complex

Inconsistent  GVN + LU



Overview

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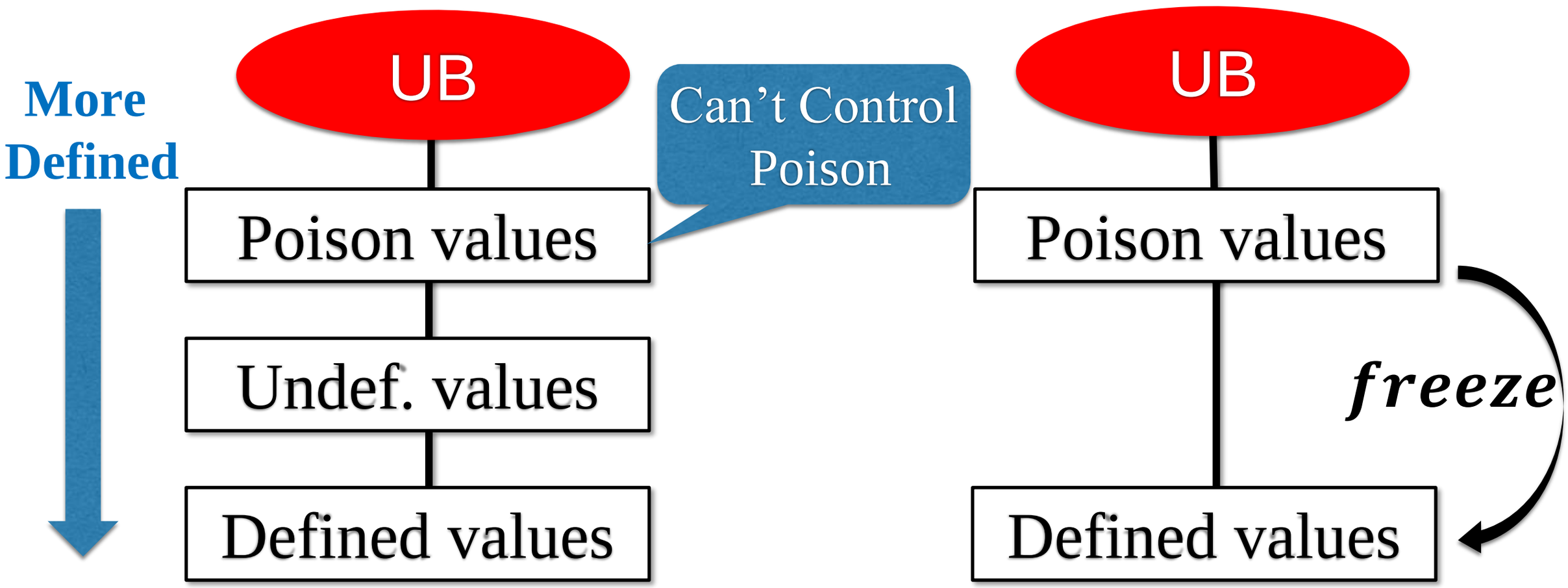
Inconsistent

GVN + LU

Our Approach

Simpler



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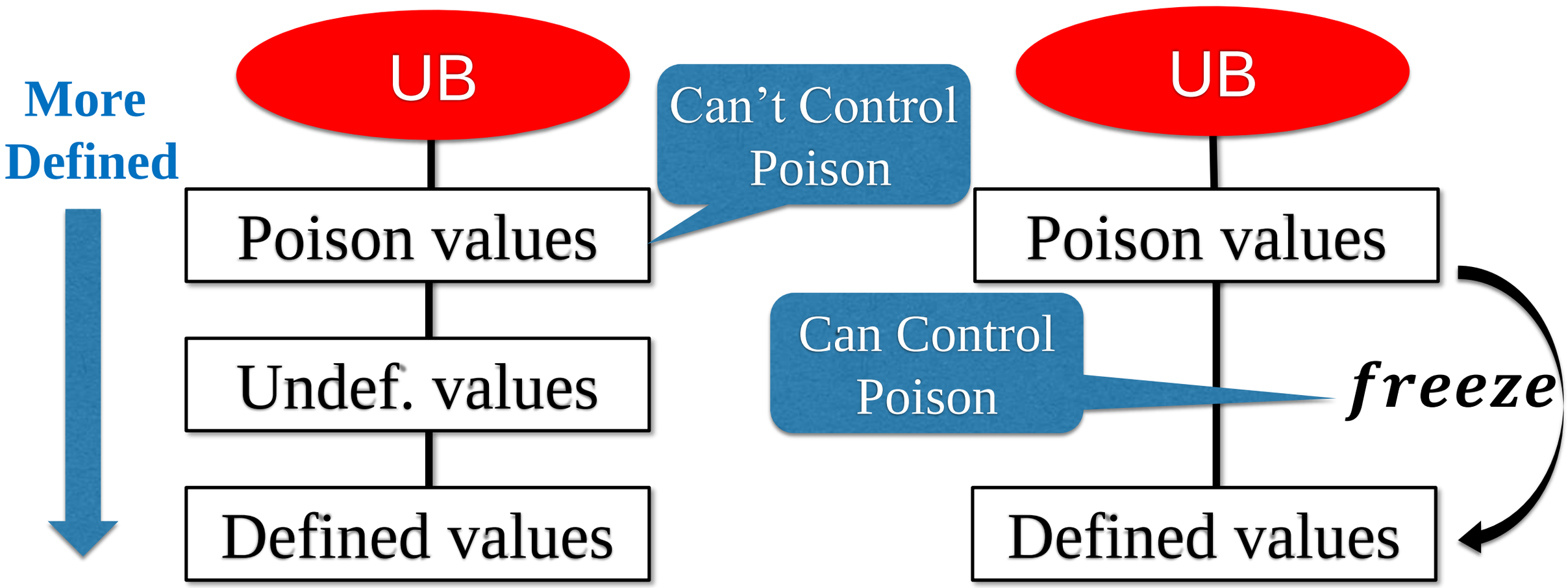


Overview

Existing Approaches

Complex

Inconsistent

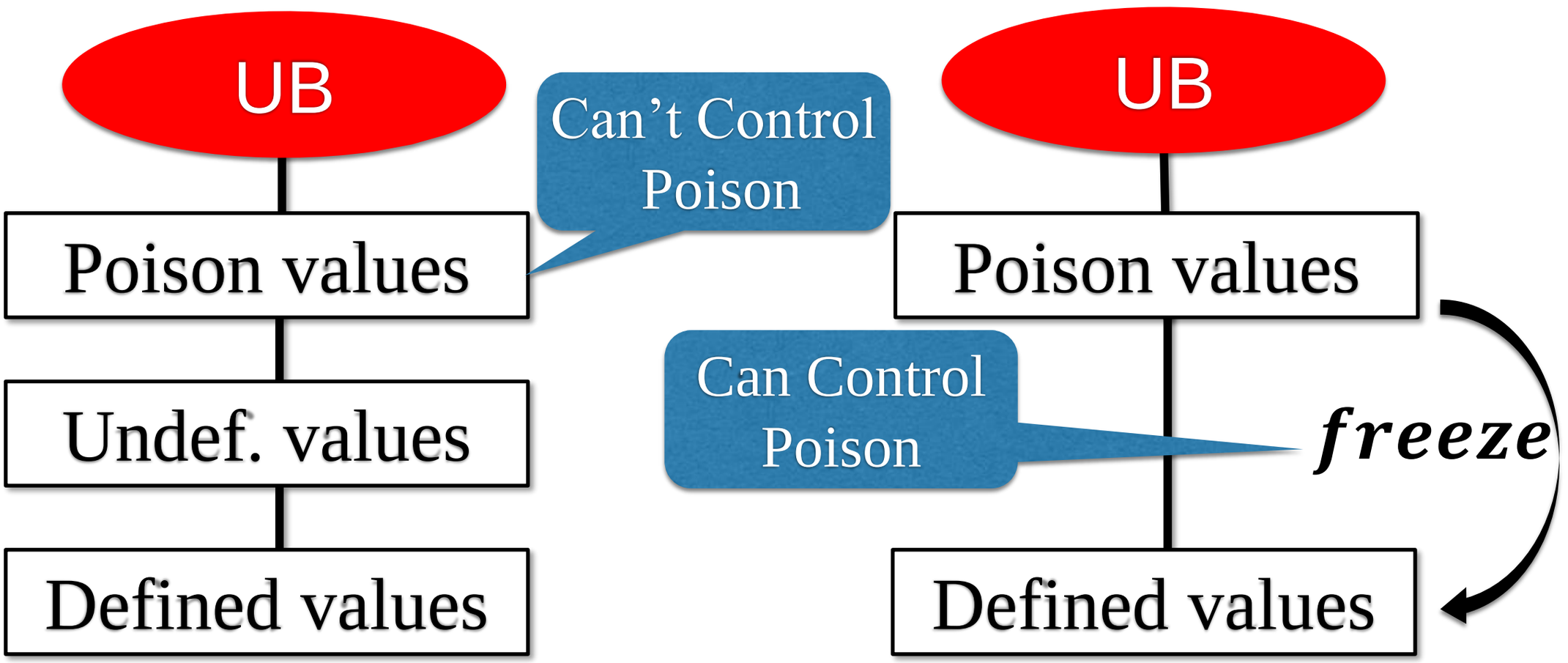
GVN + LU

Our Approach

Simpler

Consistent

More Defined



Key Idea: “Freeze”

- Introduce a new instruction

```
y = freeze x
```

- Semantics:

When `x` is a defined value: `freeze x` ⟶ `x`

When `x` is a poison value: `freeze x` ⟶ `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
  while (n > 0)
  { B }
```

Our Solution

Loop Unswitching

Our UB Model:

Branching on poison is

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0

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

Our Solution

Loop Unswitching

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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

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Compilers can control poison!

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

Freeze can also fix many other
UB-related problems.

Further Example

Hoisting Division

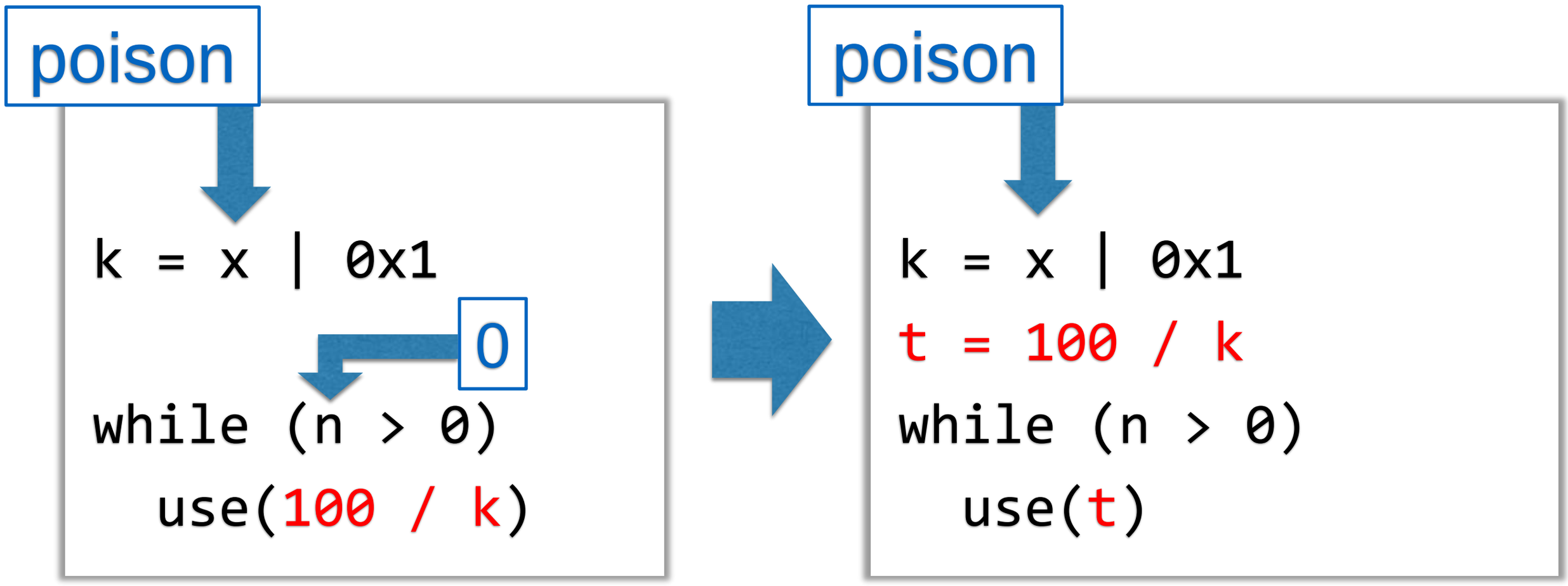
```
// bitwise-or
k = x | 0x1

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

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

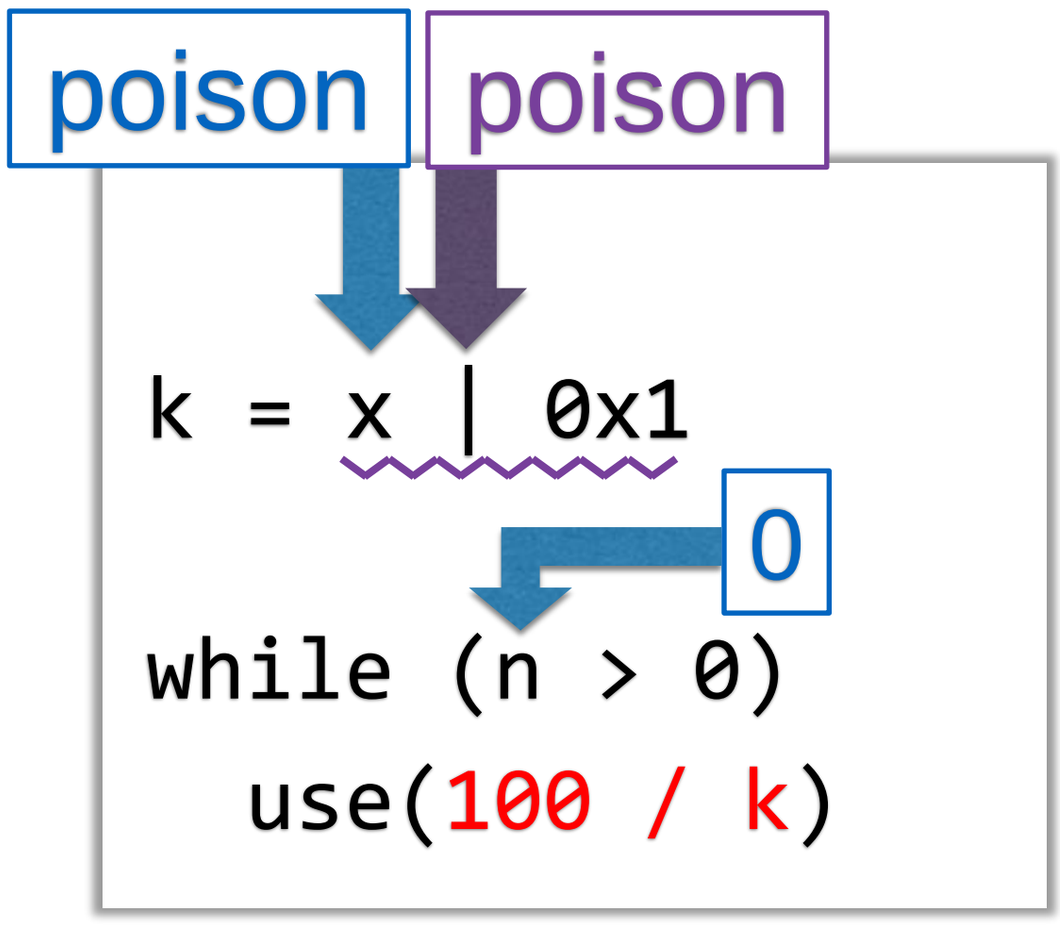
Further Example

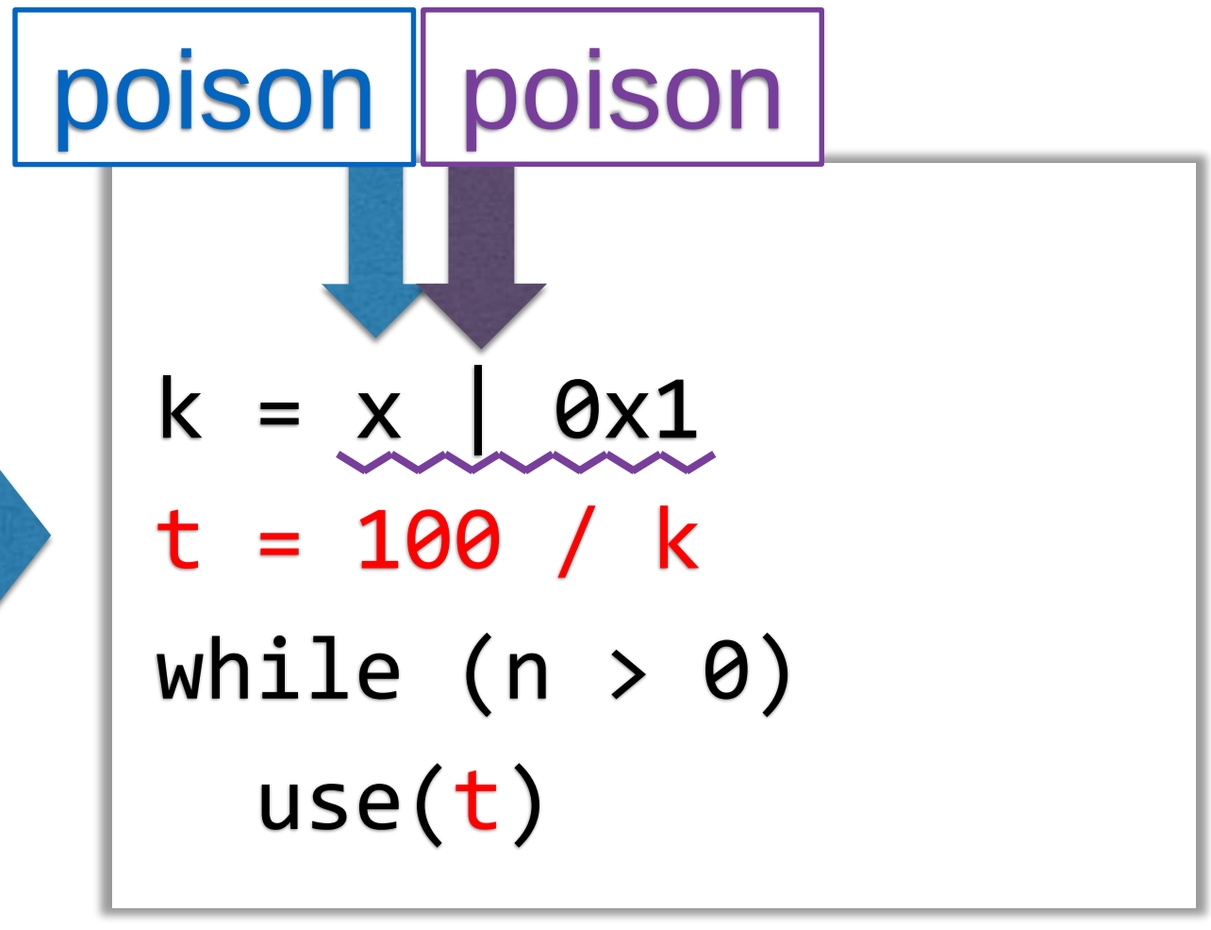
Hoisting Division



Further Example

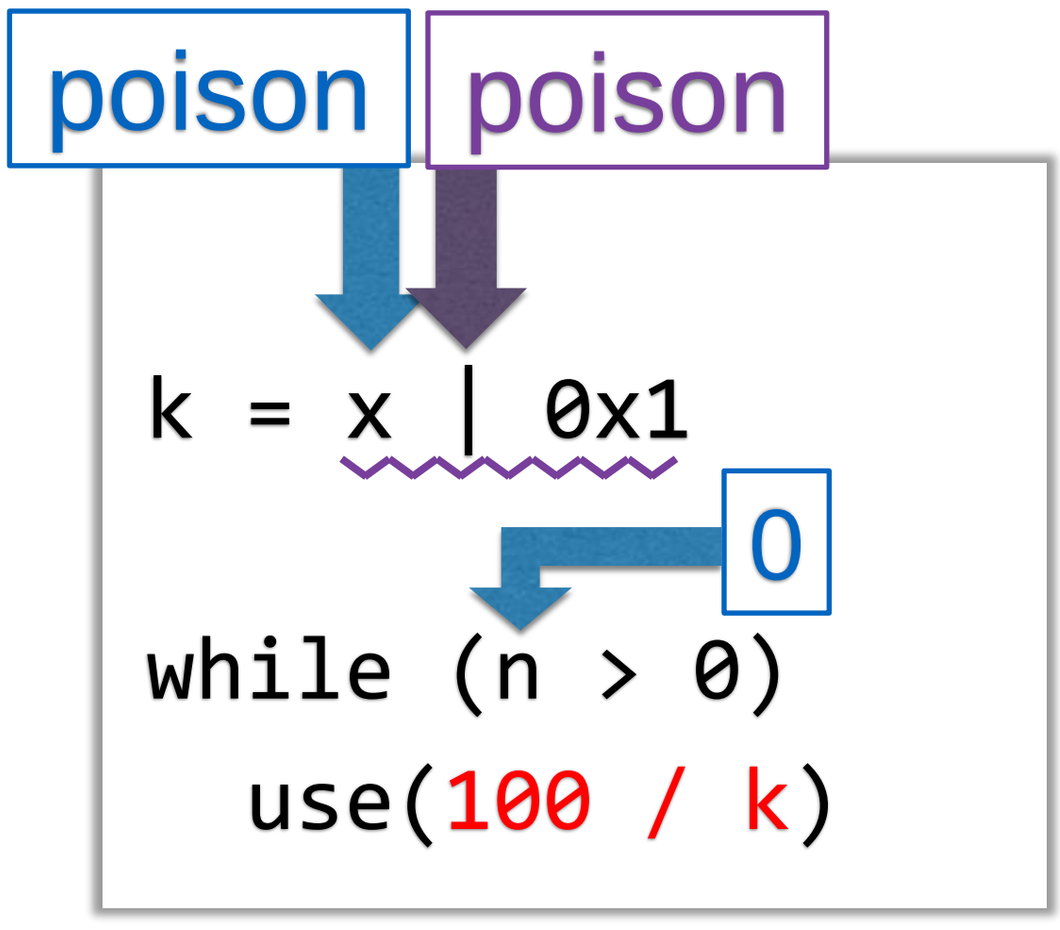
Hoisting Division

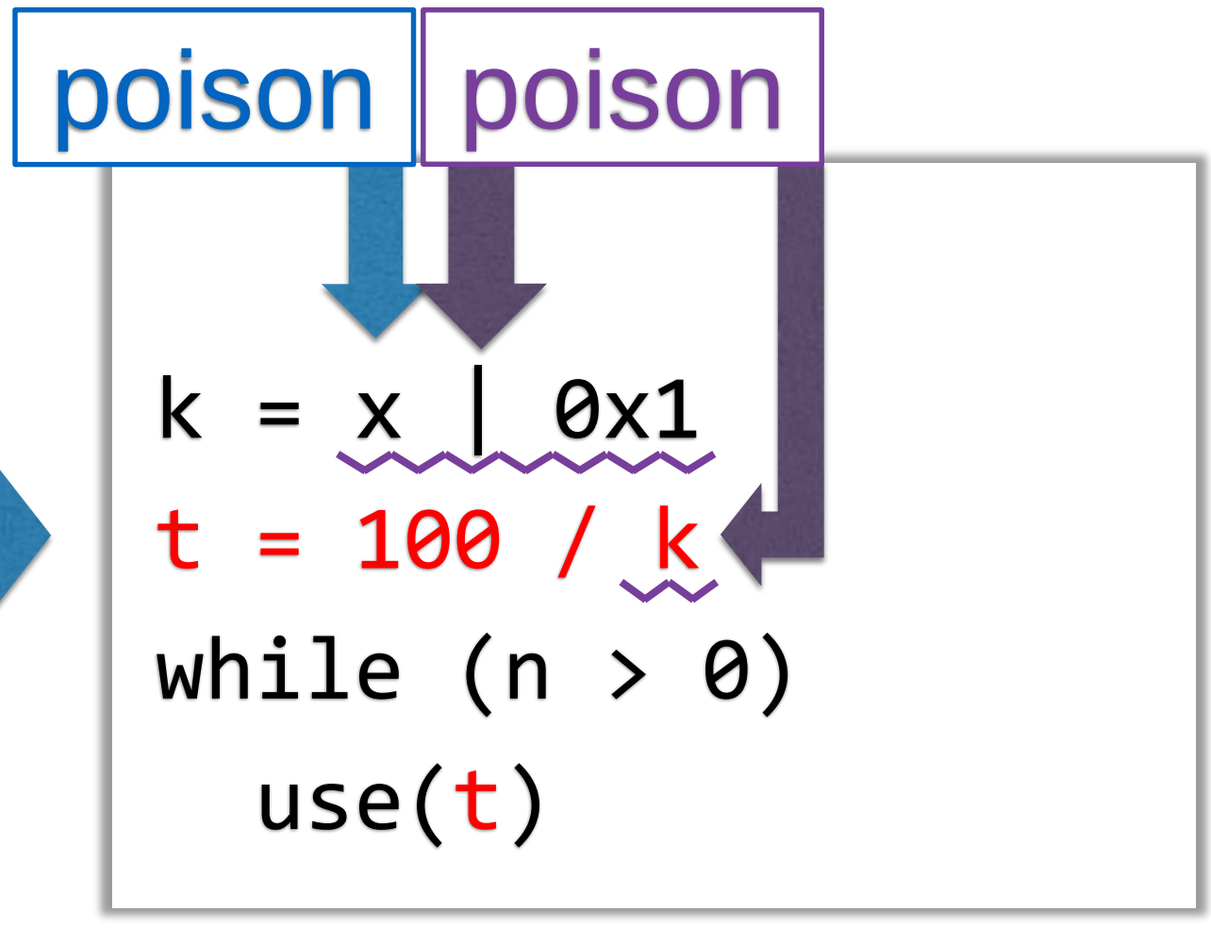




Further Example

Hoisting Division





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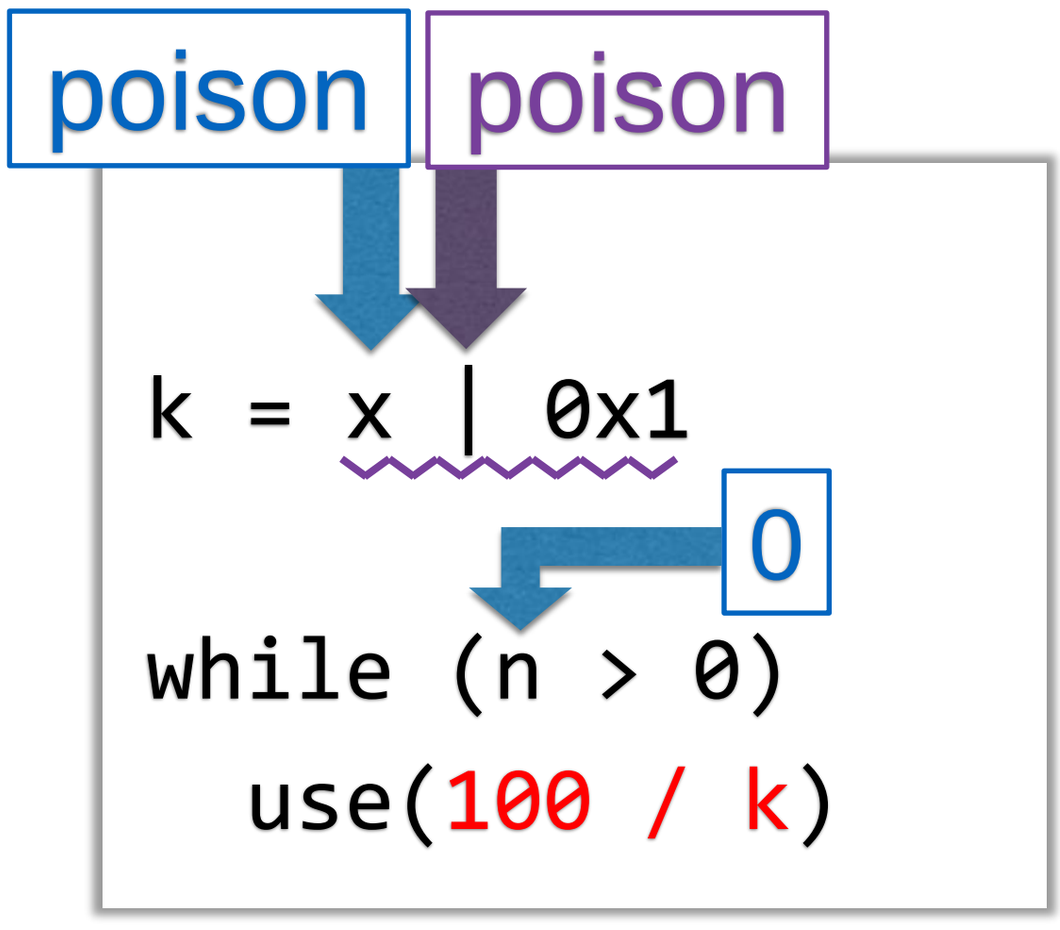
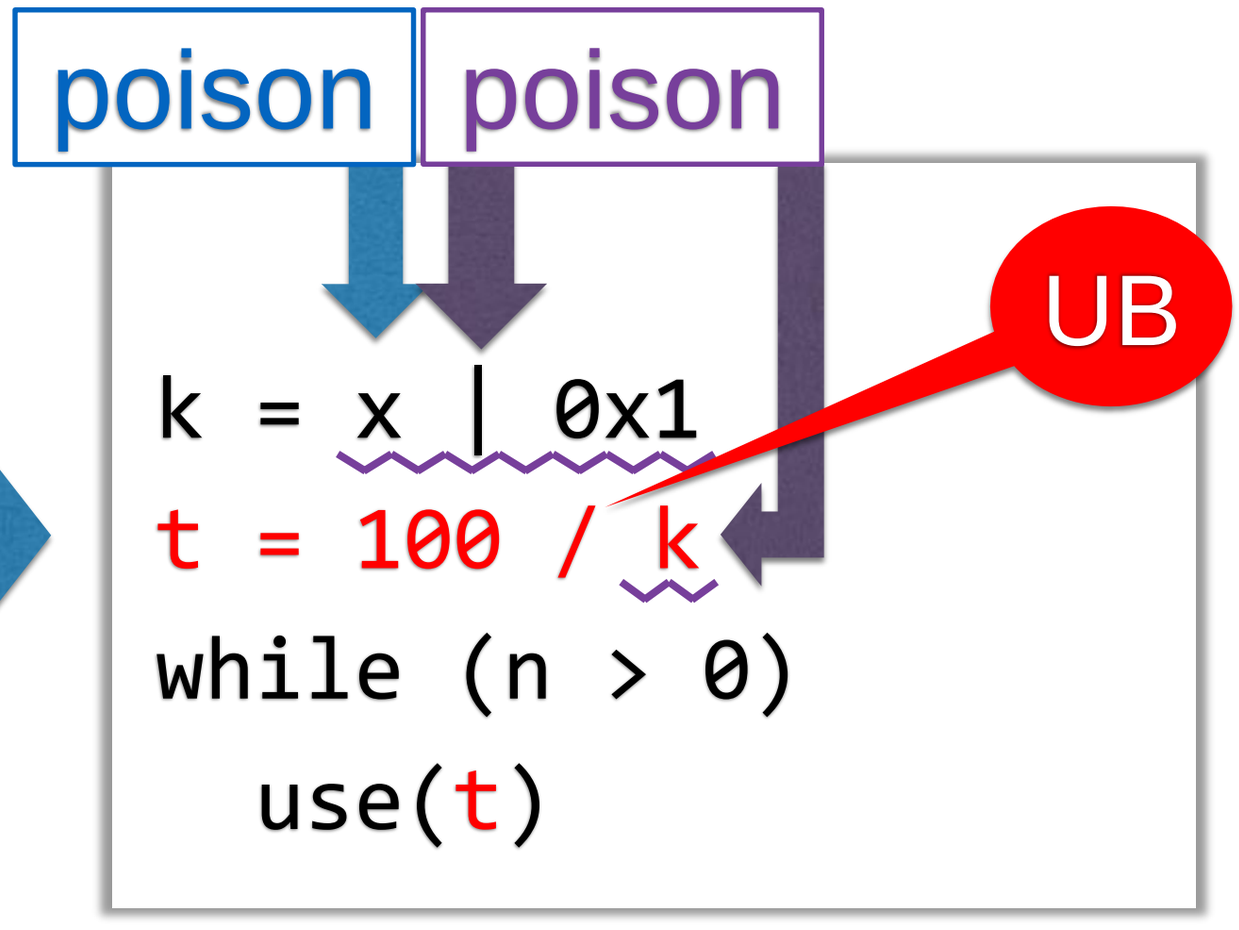
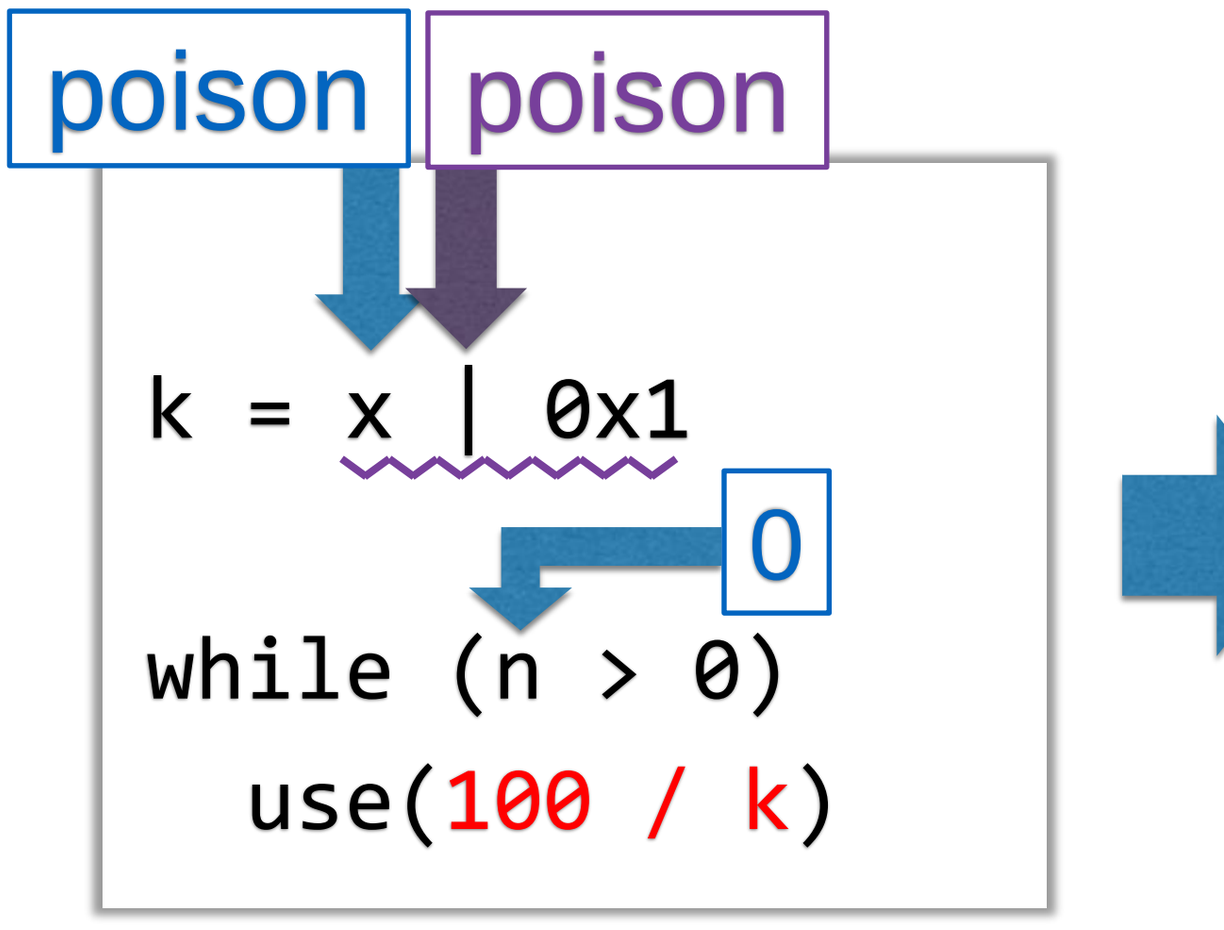


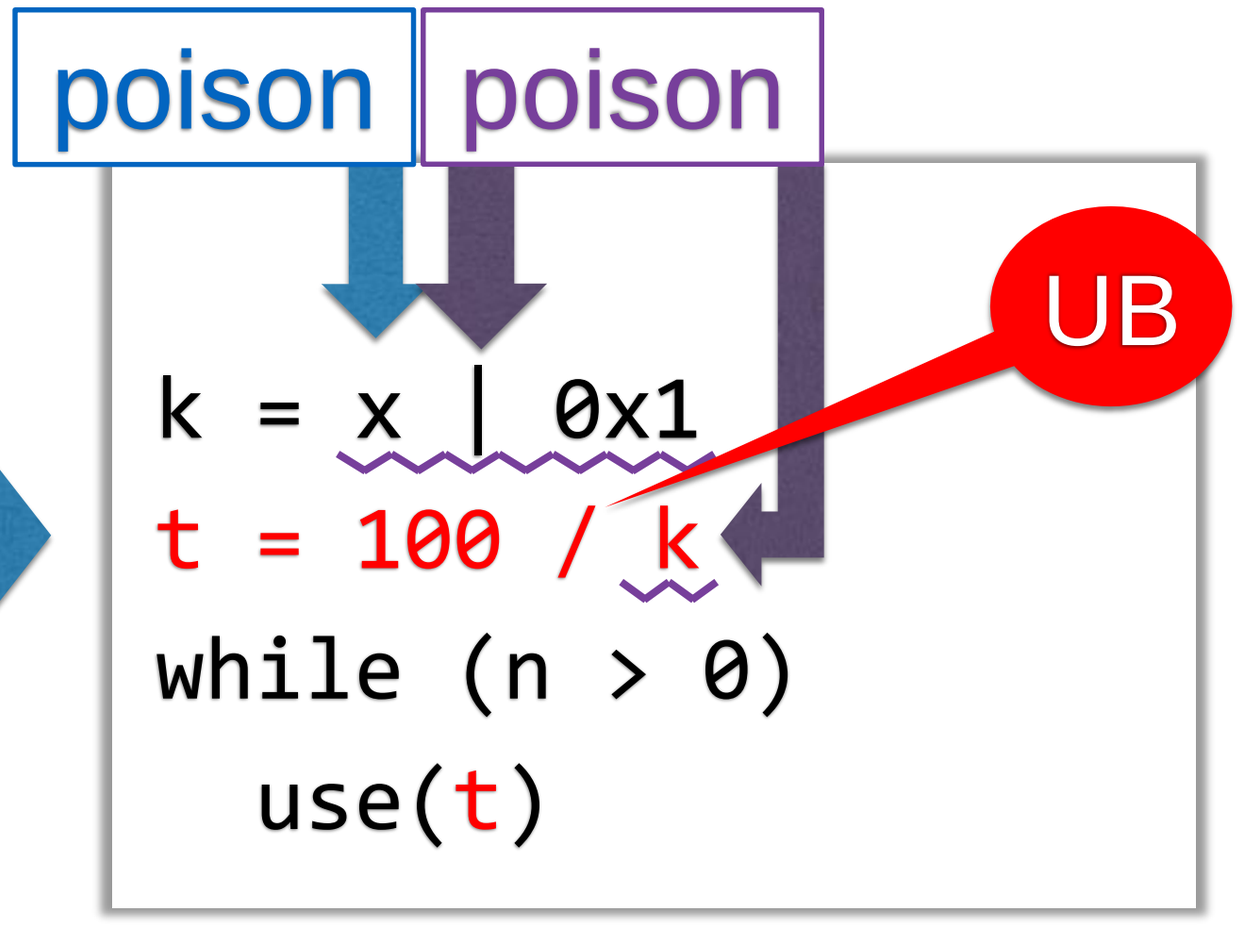


Further Example

Hoisting Division

LLVM does not currently support it.





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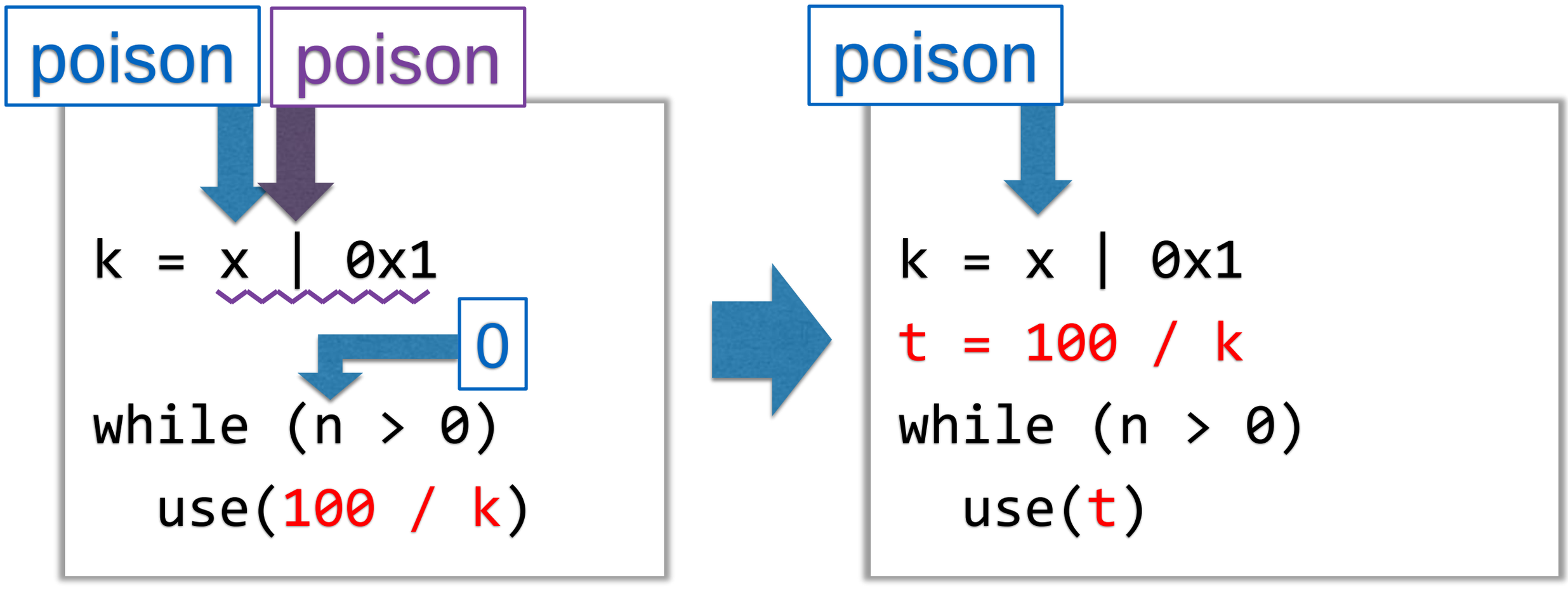
LLVM does not currently support it.



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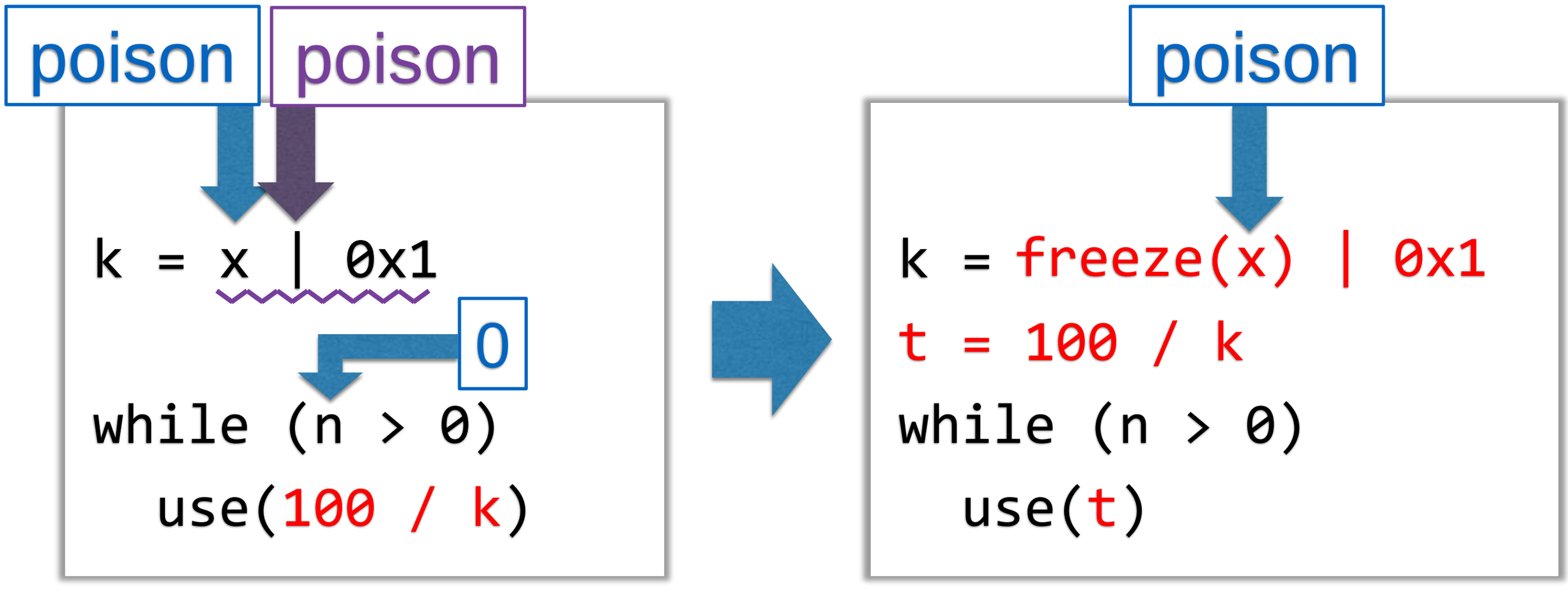

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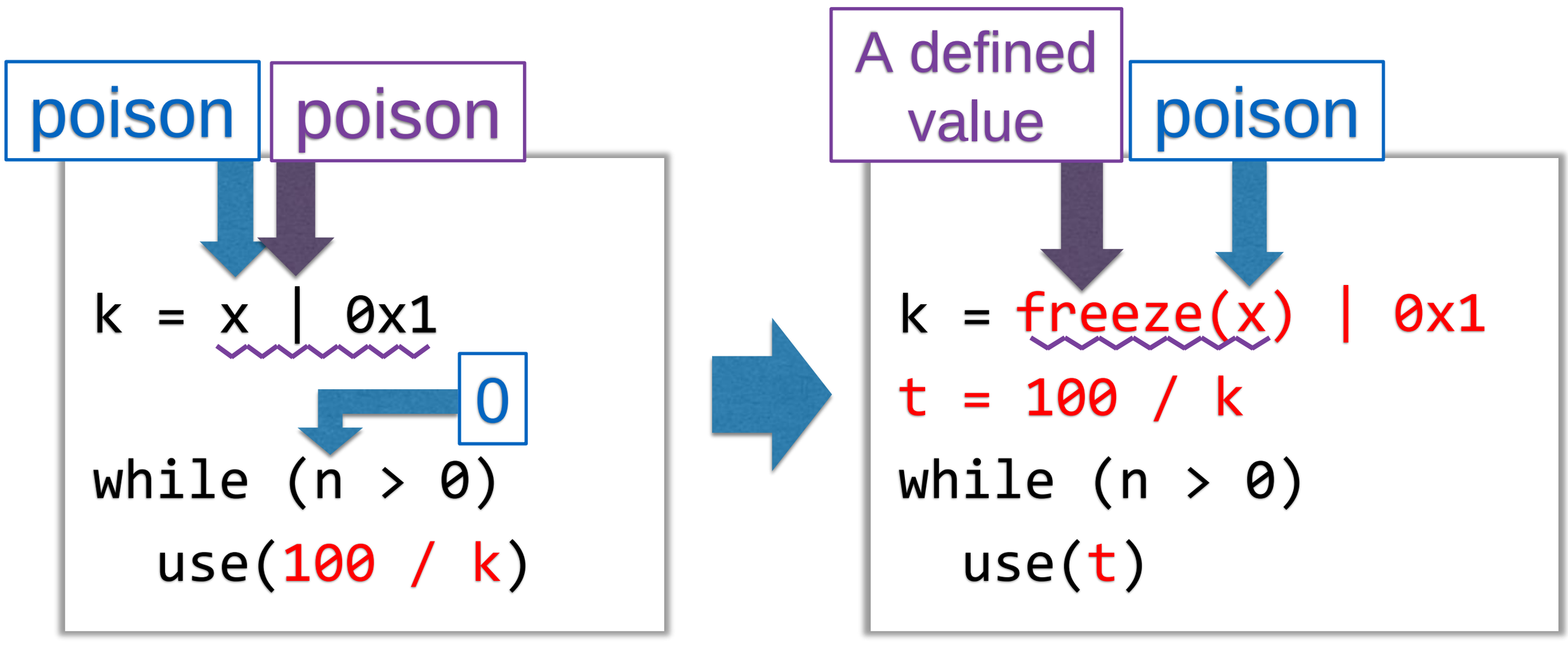

Further Example

Hoisting Division

LLVM does not currently support it.

poison poison

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

0

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

A defined value poison

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

non-zero

Further Example

Hoisting Division

Freeze can make LLVM support it!

poison poison

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

0

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

A defined value poison

```
k = freeze(x) | 0x1
t = 100 / k
```

non-zero

```
while (n > 0)
   use(t)
```

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

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Conclusion

- Modern compilers' UB models cannot support some textbook optimizations.

- We propose "freeze" to fix such problems.

- Freeze has little impact on performance.