CMPT 745
Software Engineering

Dynamic Analysis

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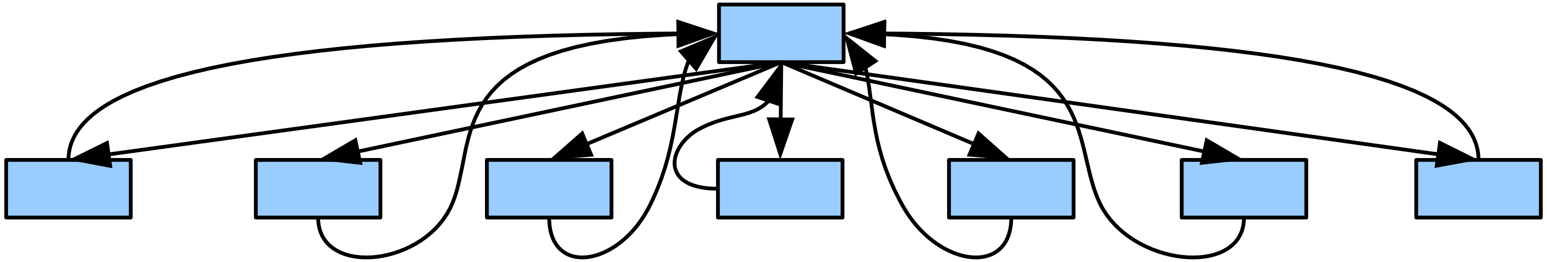
  - Tolerate errors
  - Manage memory / resources.

e.g. Reverse Engineering

Static CFG (from e.g. Apple Fairplay):



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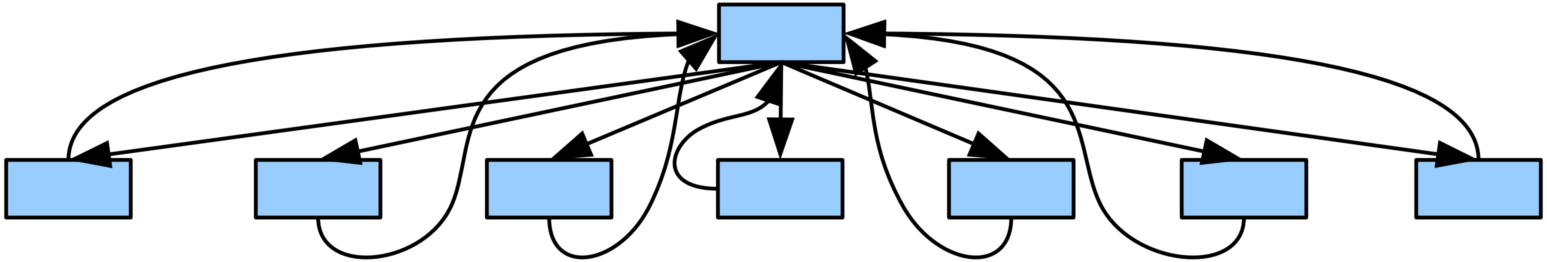

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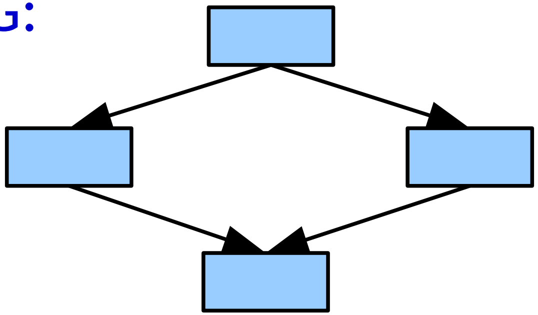
Dynamically Simplified CFG:



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Some analyses only make sense *online*.
Why?

Simple Idea: Basic Block Profiling

Knowing where we are spending time is useful:

- **Goal:** *Which basic blocks execute most frequently?*

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Profiling is a common dynamic analysis!

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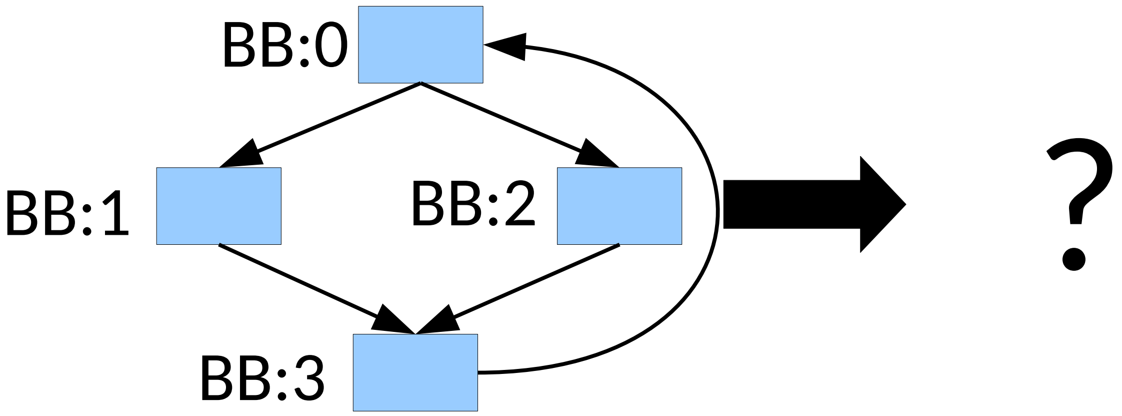

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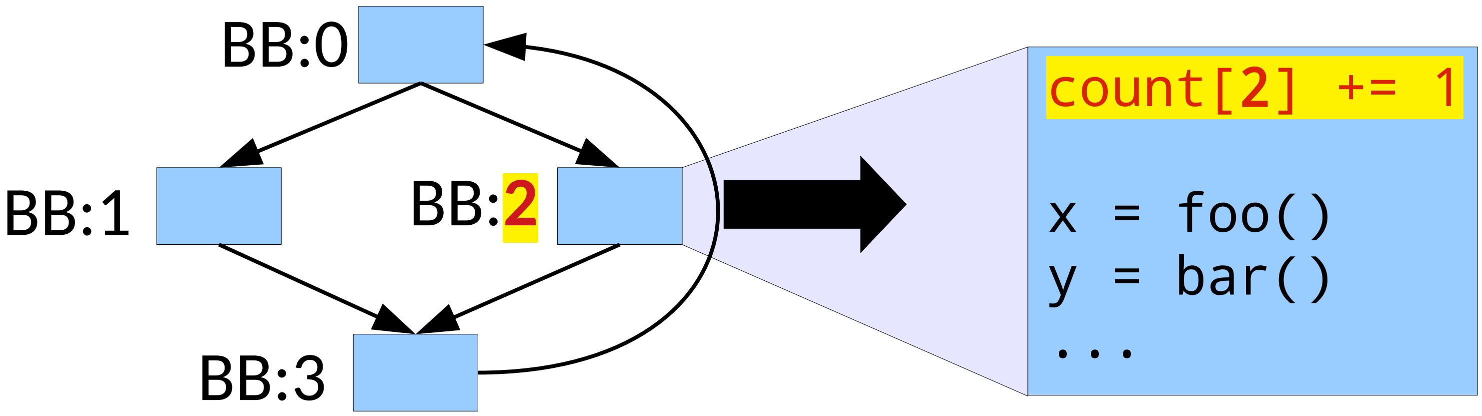

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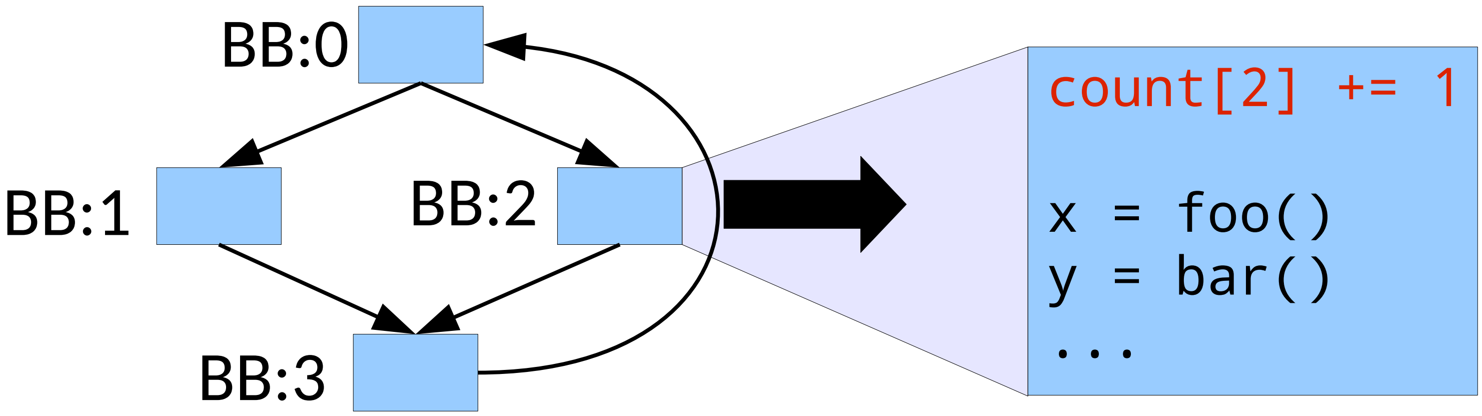

Start:

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for i in BBs:
  count[i] = 0
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End:

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for i in BBs:
  print(count[i])
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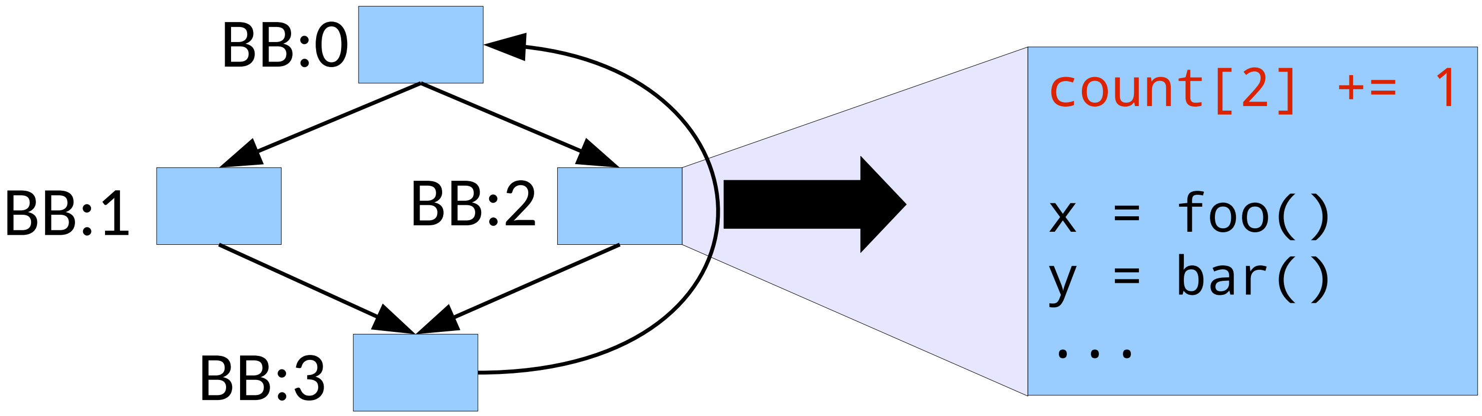

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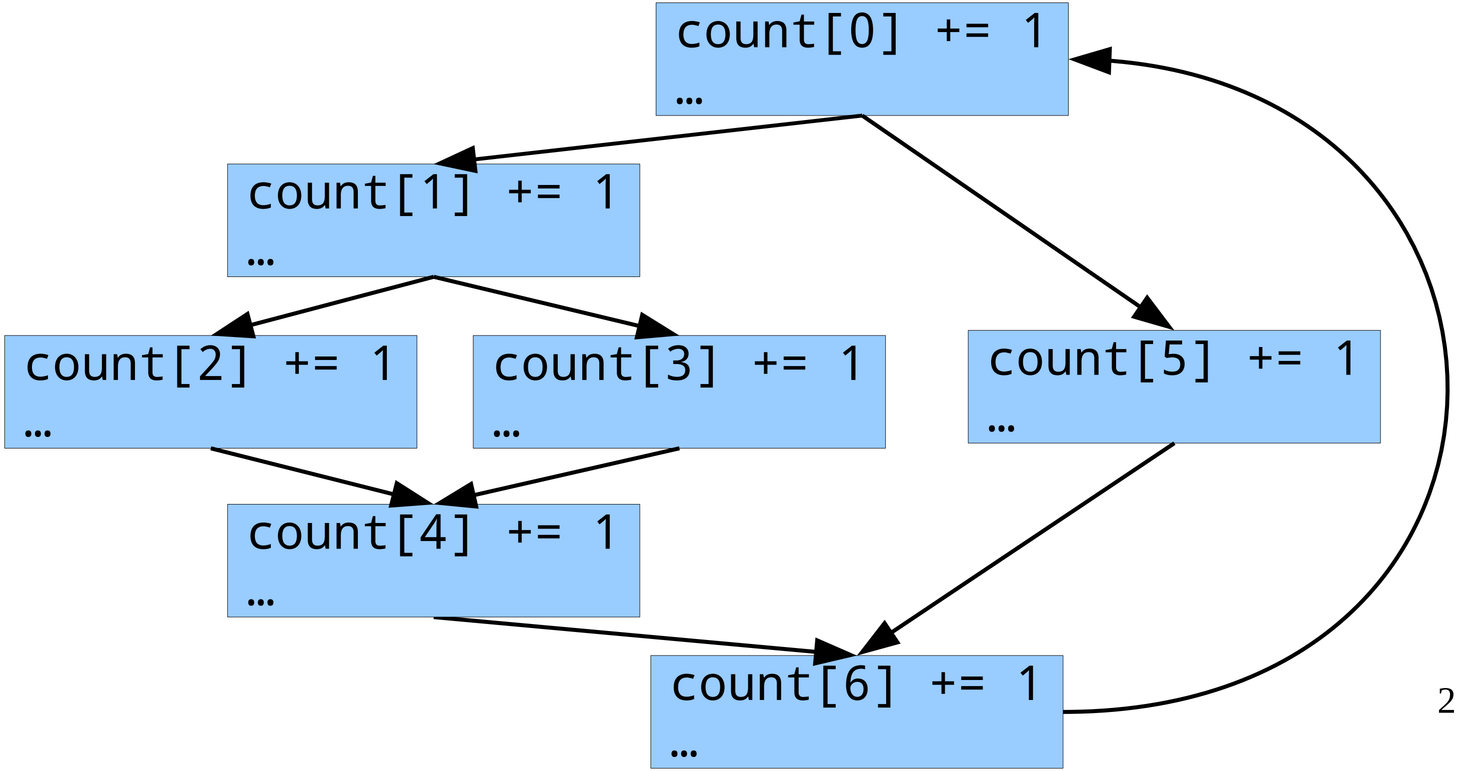

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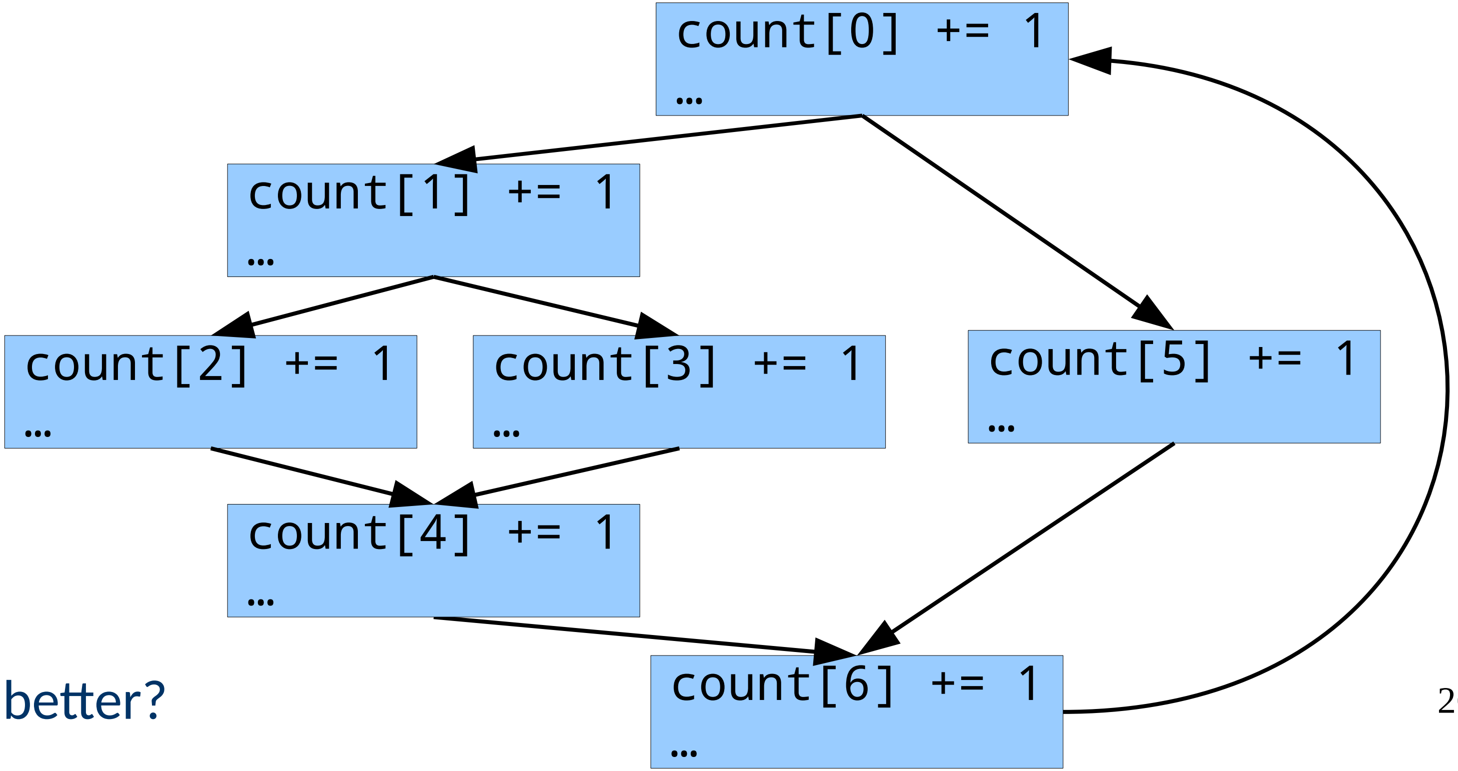

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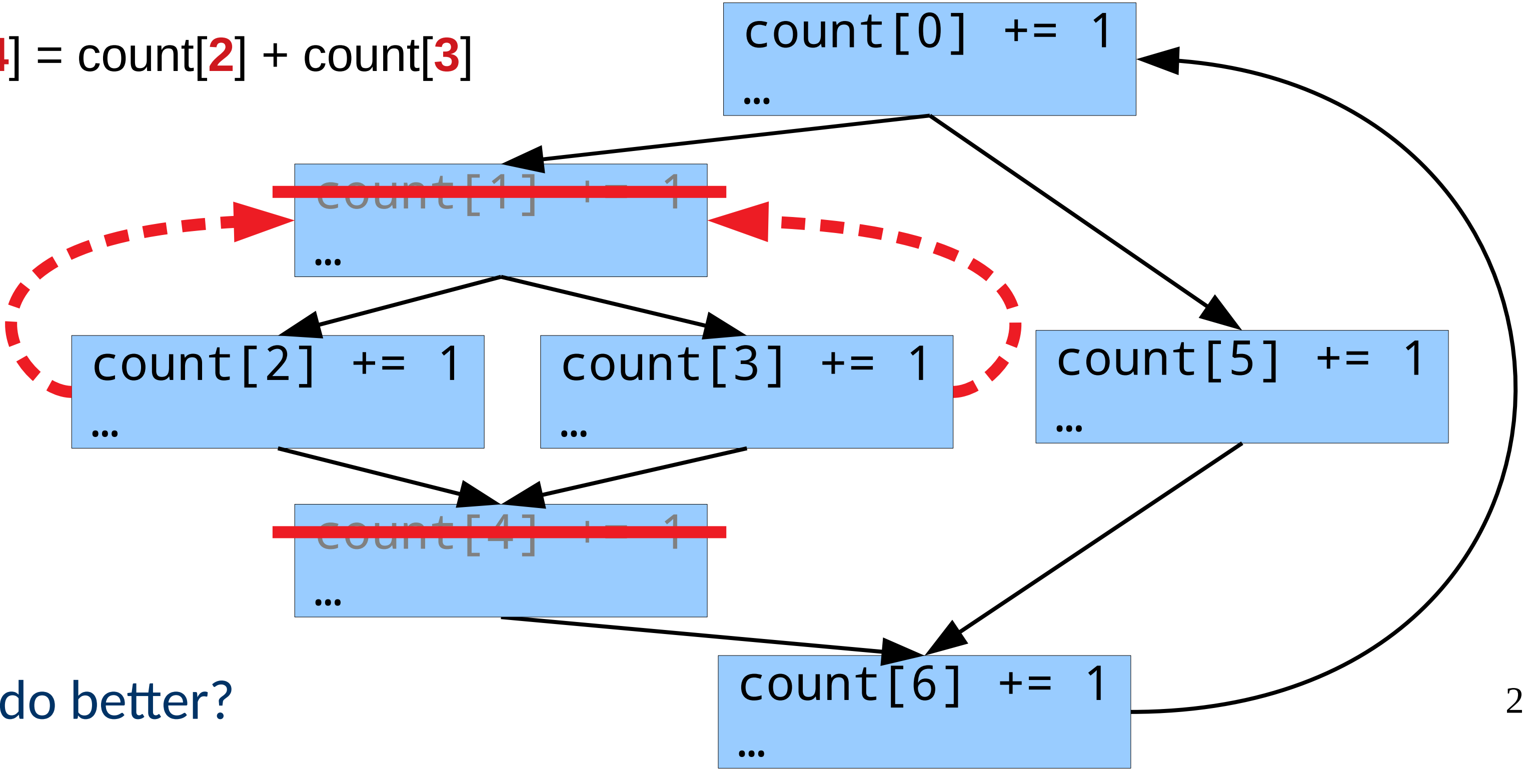

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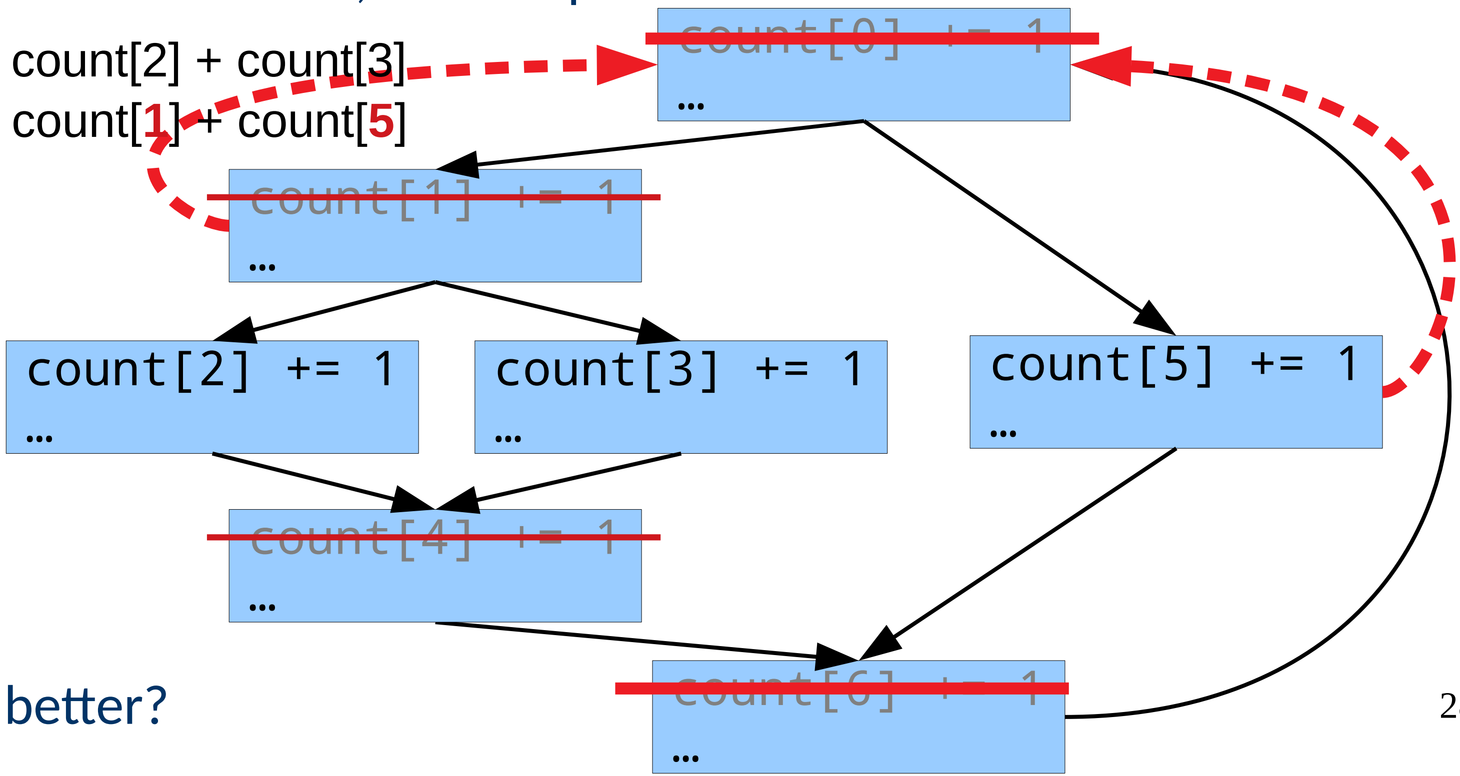

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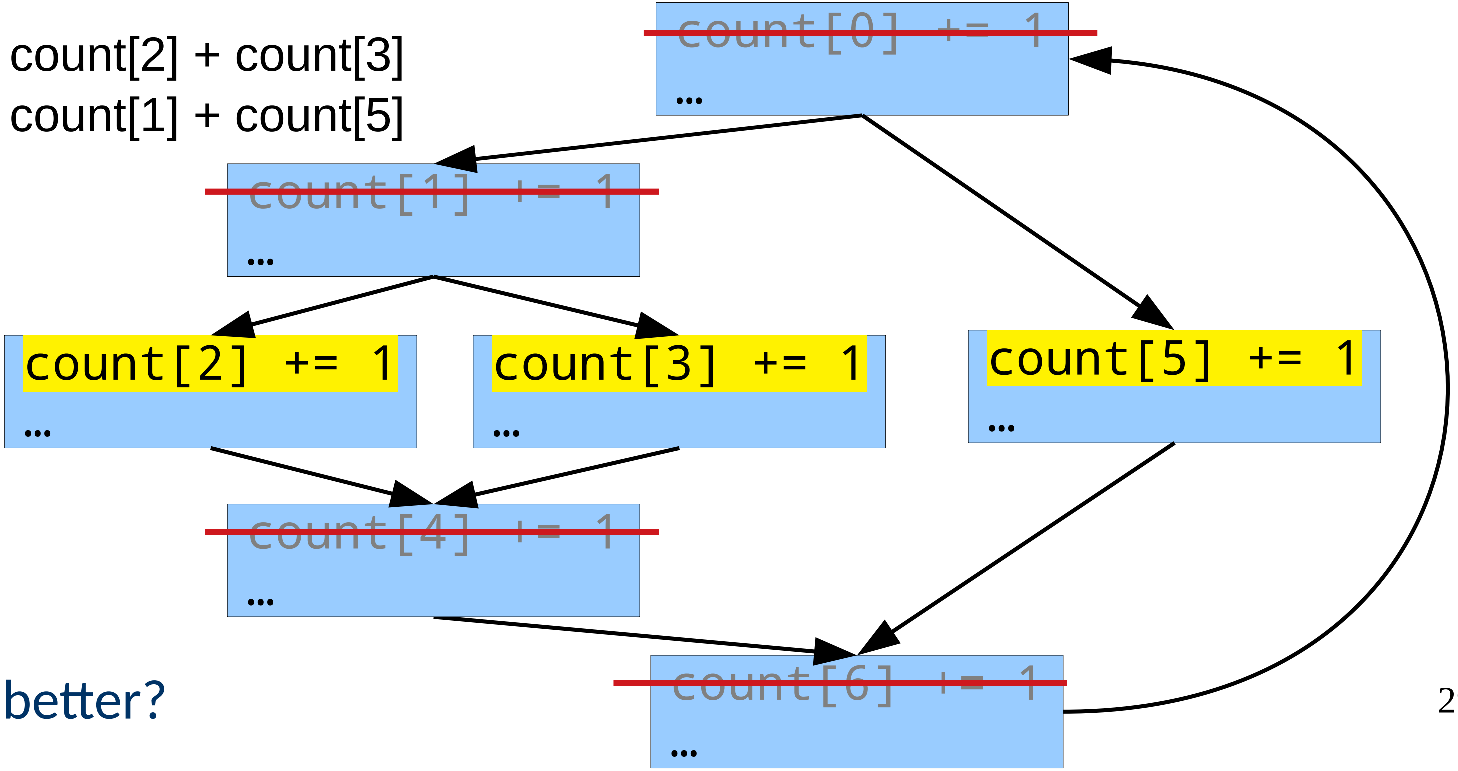

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- *Black Box* Dynamic Analysis

Phases of Dynamic Analysis

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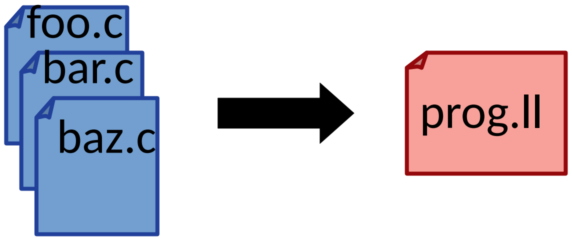
Very, ***very*** common mistake to mix 1 & 2.

Static Instrumentation

1) Compile whole program to IR



Static Instrumentation

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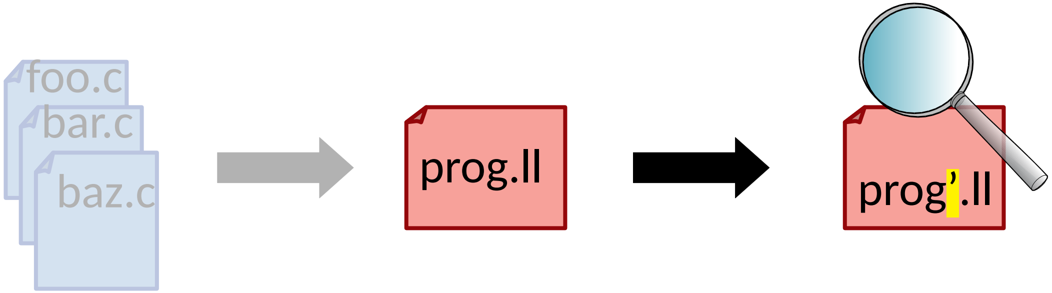

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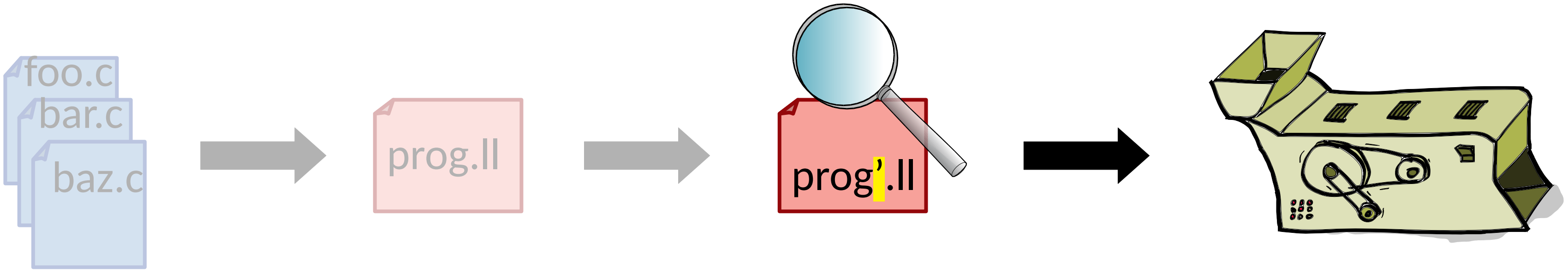

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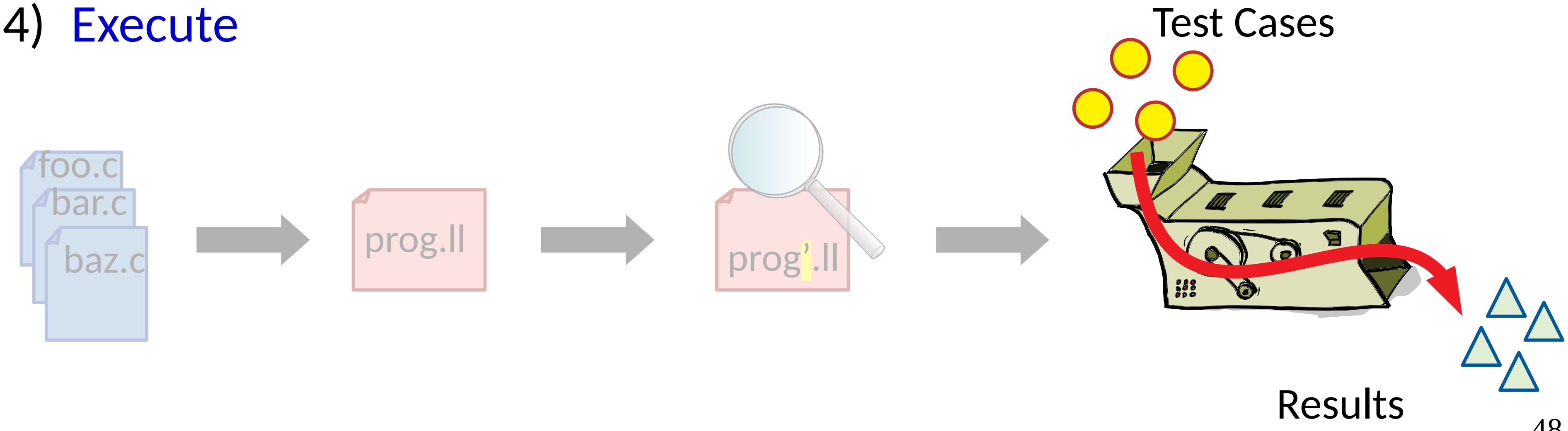

Dynamic Binary Instrumentation (DBI)

1) Compile program as usual
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(Valgrind, PIN, Qemu, etc)

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valgrind --tool=memcheck ./myBuggyProgram
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3) Instrument & execute in same command:
   - Fetch & instrument each basic block individually
   - Execute each basic block

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- Intuitively, even just testing is a dynamic analysis
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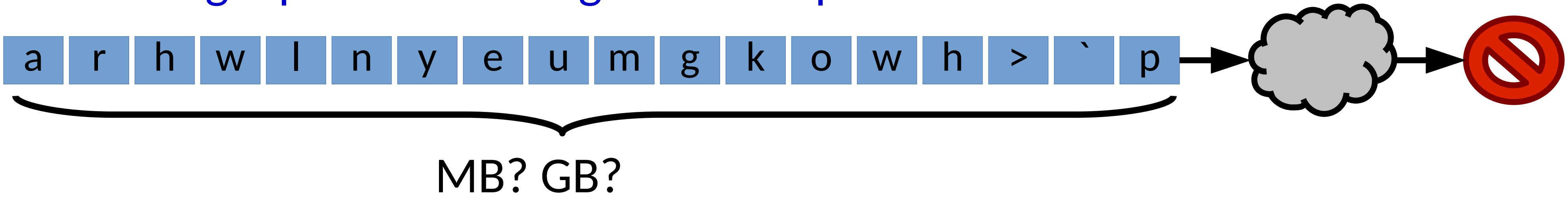
- But even that is interesting to consider….

Bug reports are problematic

- Failing inputs can be large and complex



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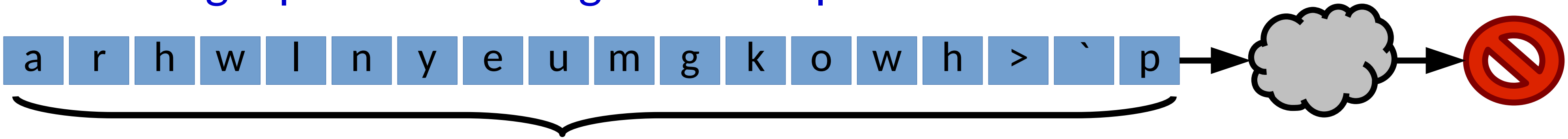

MB? GB?

What is relevant and essential to the bug?

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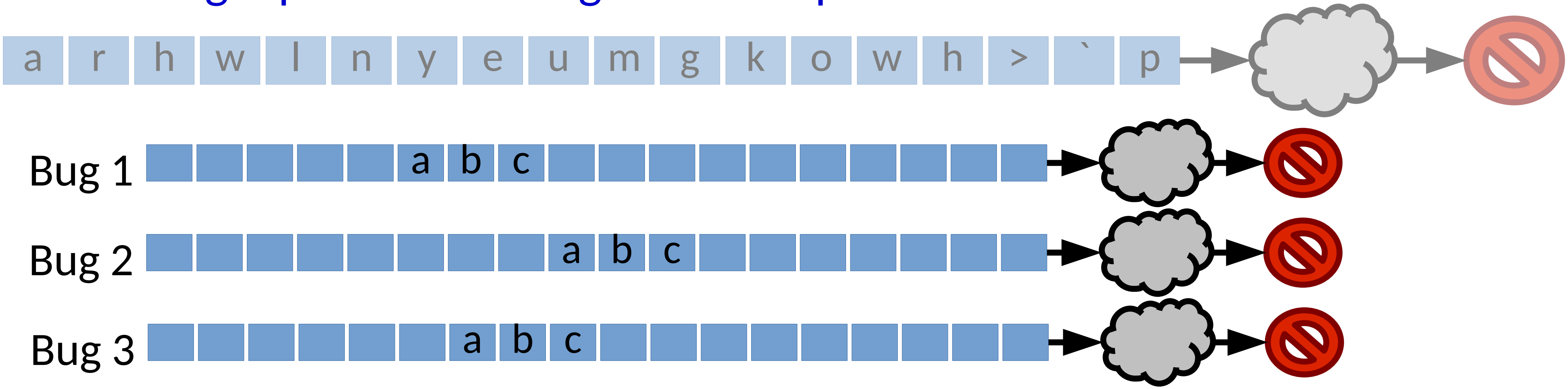

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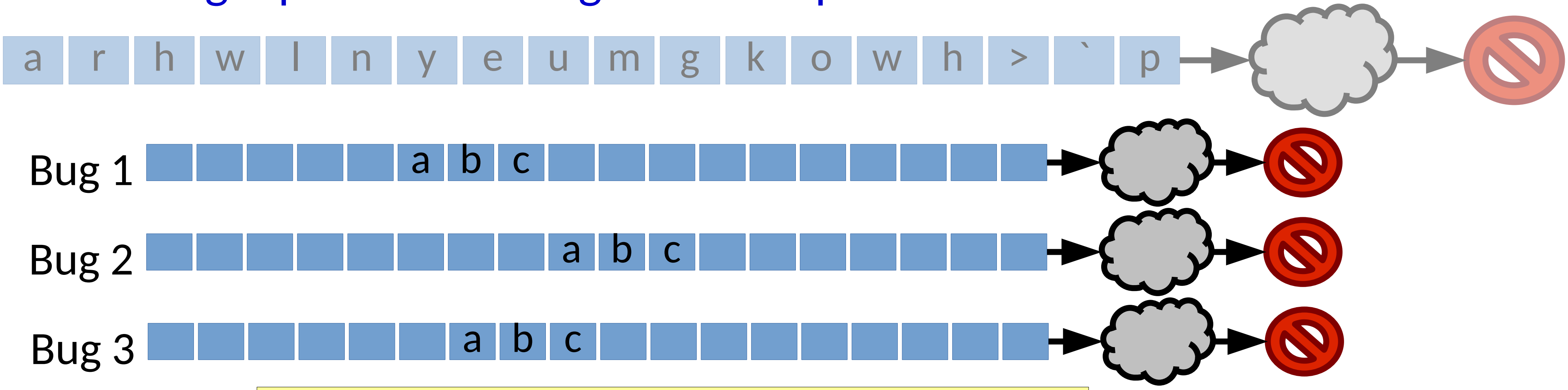

1) Are these reports the same bug?
2) Can we make it easier to reproduce?

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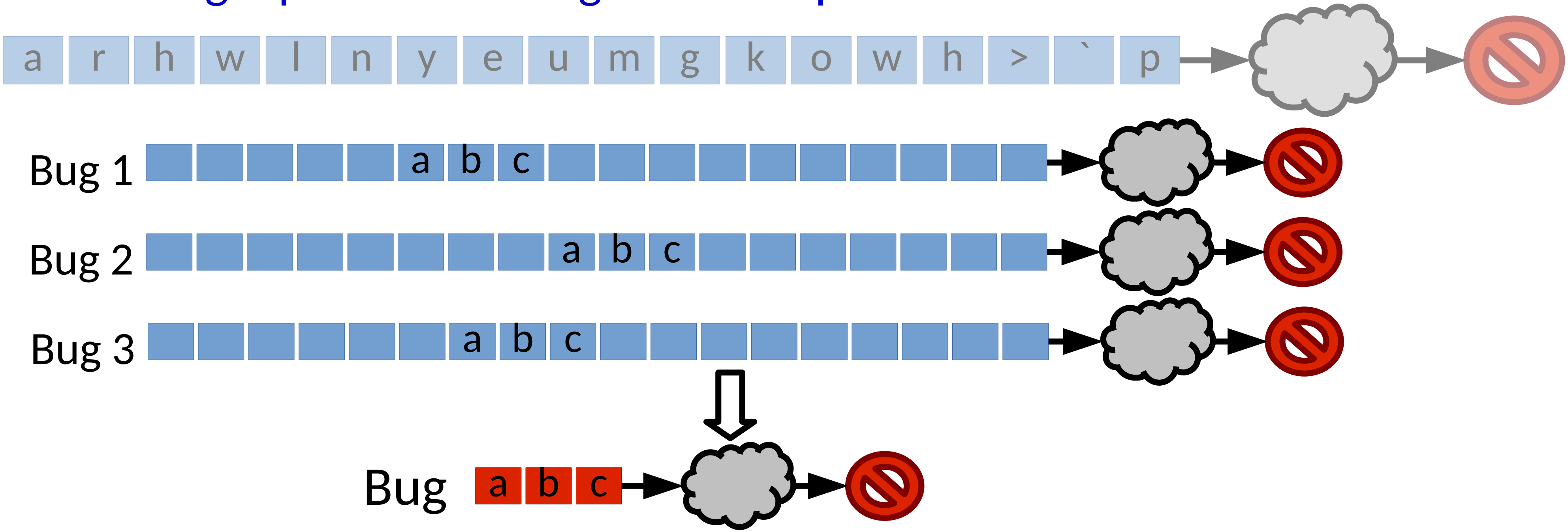

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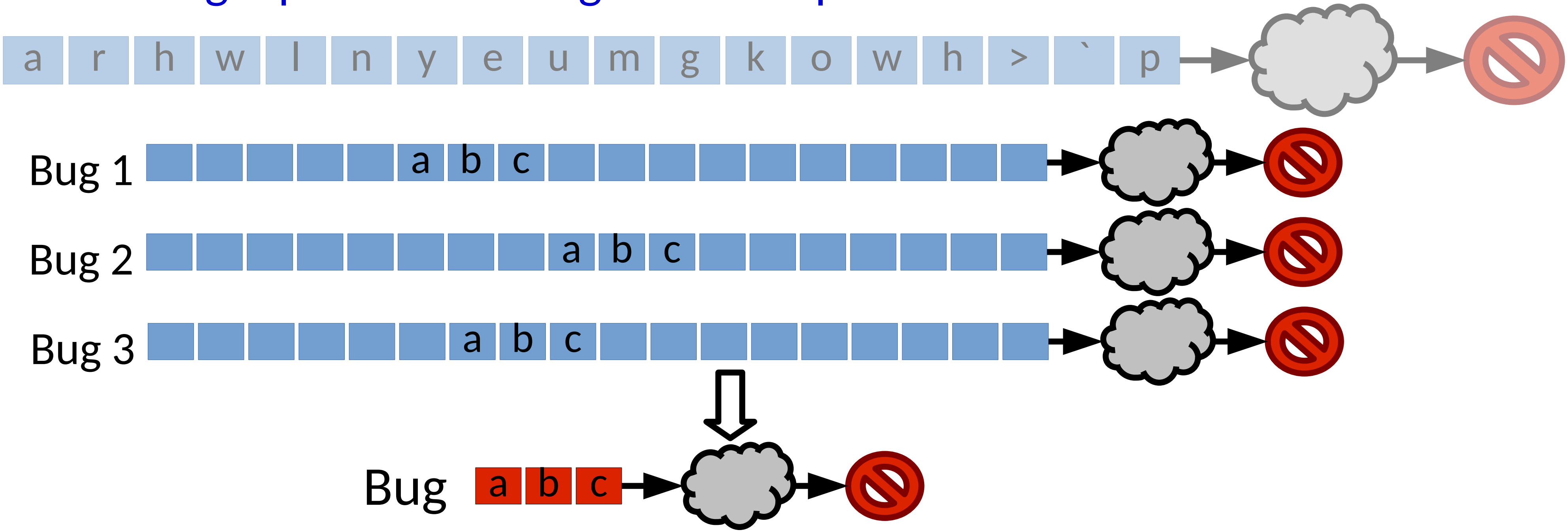

1) Same? Yes!
2) Easier? Yes! And easier to understand!

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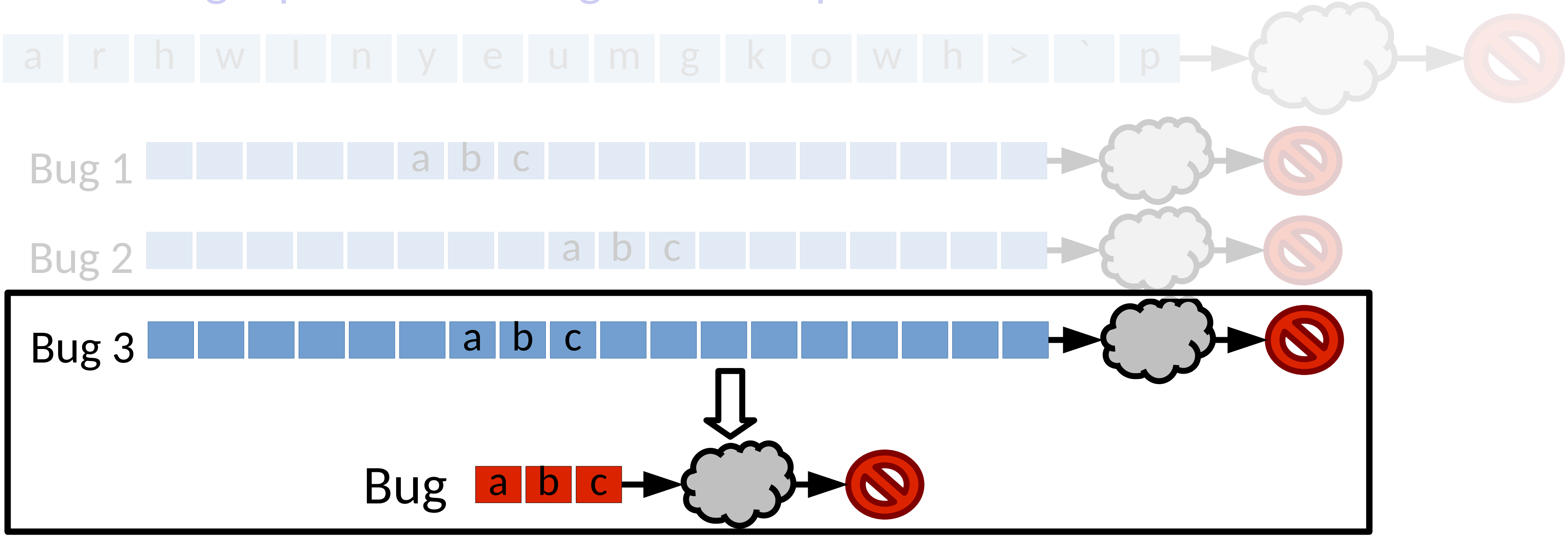
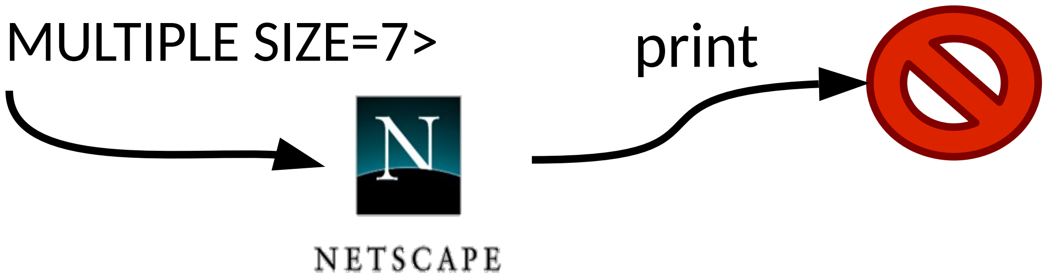


Test Case Reduction: finding smaller test cases that reproduce a failure

Classically – Delta Debugging

<SELECT NAME="priority" MULTIPLE SIZE=7>



http://en.wikipedia.org/wiki/File:Netscape_2_logo.gif

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Intuition: trial and error
1) Start w/ a failing text configuration **c**

Classically – Delta Debugging

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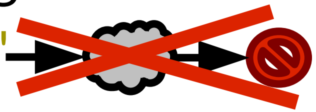
- Global Minimum: $c : \forall\ |c'| < |c|,\ c'$ 

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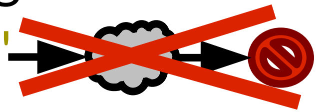
- Global Minimum: $c : \forall\ |c'| < |c|,\ c'$ 

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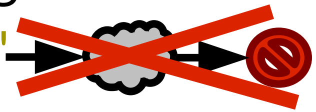
- Global Minimum: $c : \forall\ |c'|<|c|, c'$ 

Completely impractical! Why?

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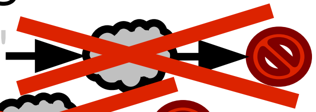
- Global Minimum: $c : \forall\ |c'| < |c|,\ c'$ 
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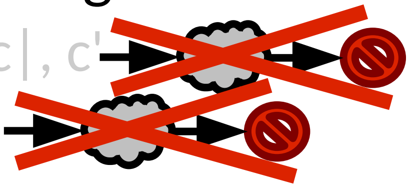

How does this differ from a global minimum?
Is it still problematic?

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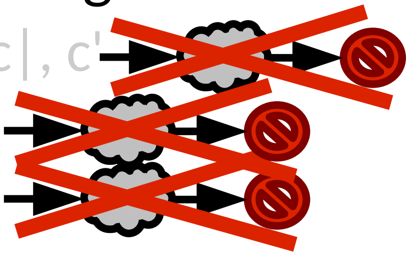
- 1-Minimal: c: ∀ δ ∈ c, (c-{δ})



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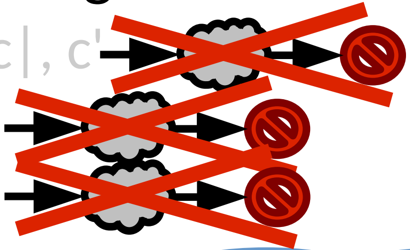

No one element can be removed
and still reproduce the failure

Classically – Delta Debugging

<SELECT NAME="priority" MULTIPLE SIZE=7>

Intuition: trial and error
1) Start w/ a failing text configuration **c**
2) Try removing subsets (Δ) of input elements ({δ})
3) Failure still exists → new input is "better"
4) Repeat on the new input

When do we stop? / What is our goal?

- Global Minimum: $c : \forall \ |c'| < |c|, c'$
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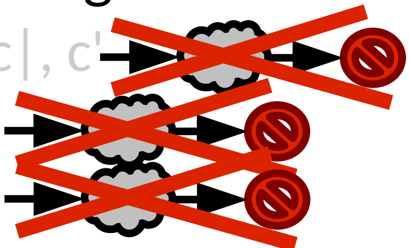
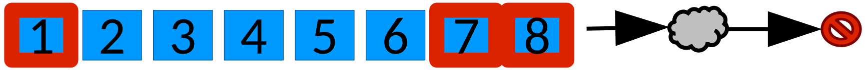


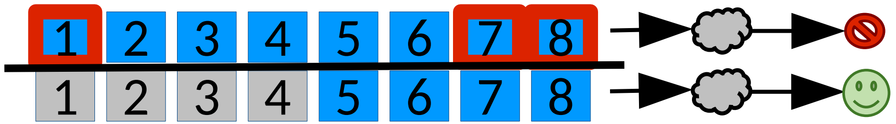
This is the classic goal.
In practice, the formalism may not pay for itself in terms of *quality* or *efficiency*! (Be pragmatic!)

Classically – Delta Debugging



Does binary search work?

Classically – Delta Debugging



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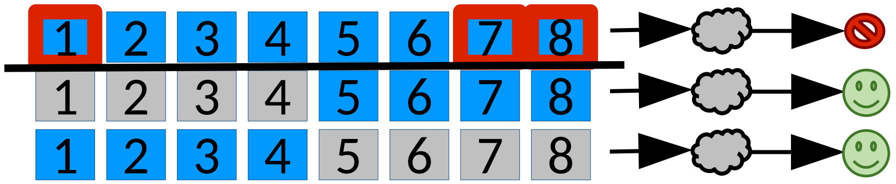
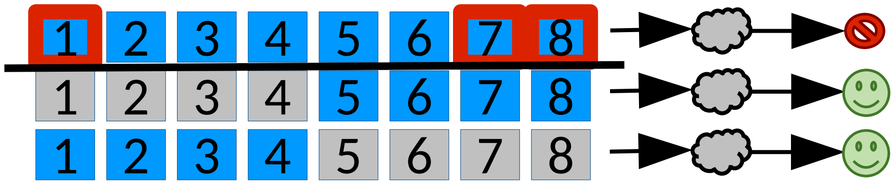


So what should we do?

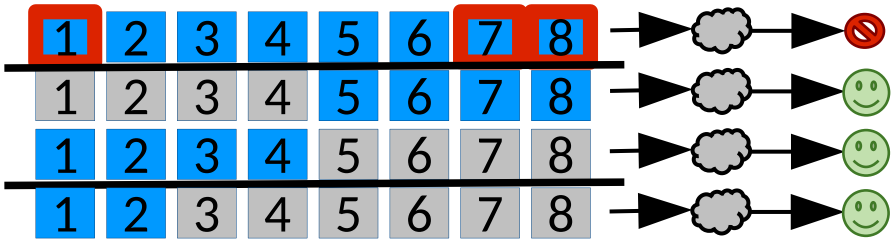
Classically – Delta Debugging



So what should we do?

We refine the granularity

Classically – Delta Debugging



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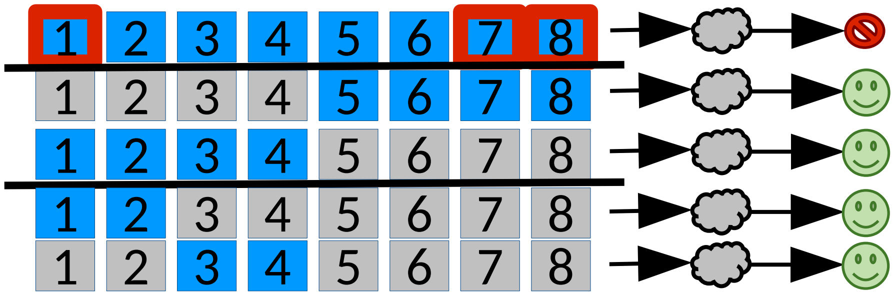

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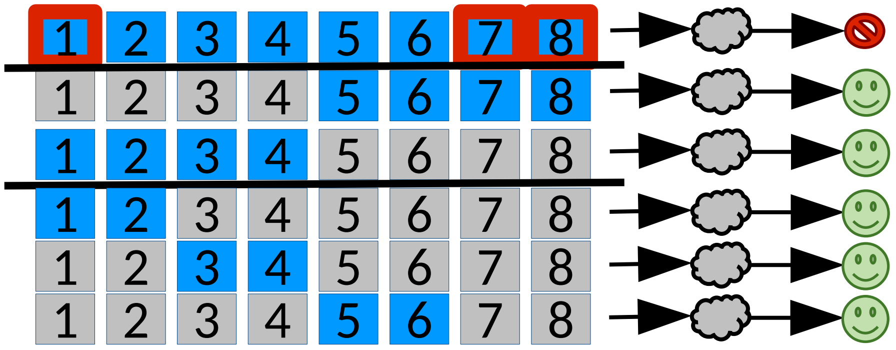

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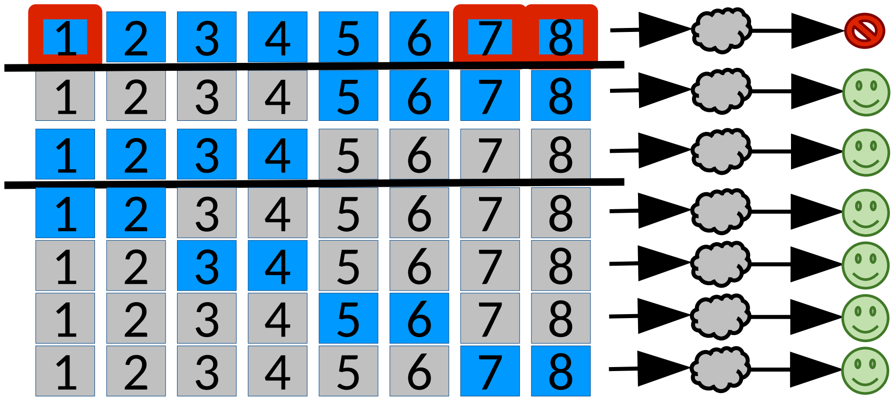

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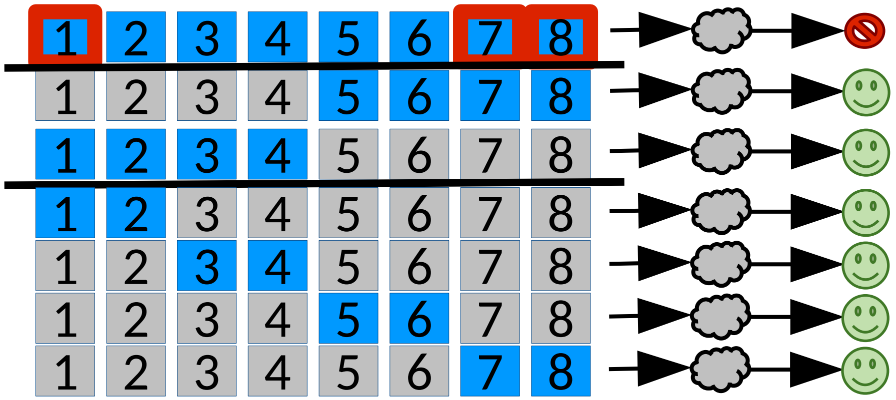
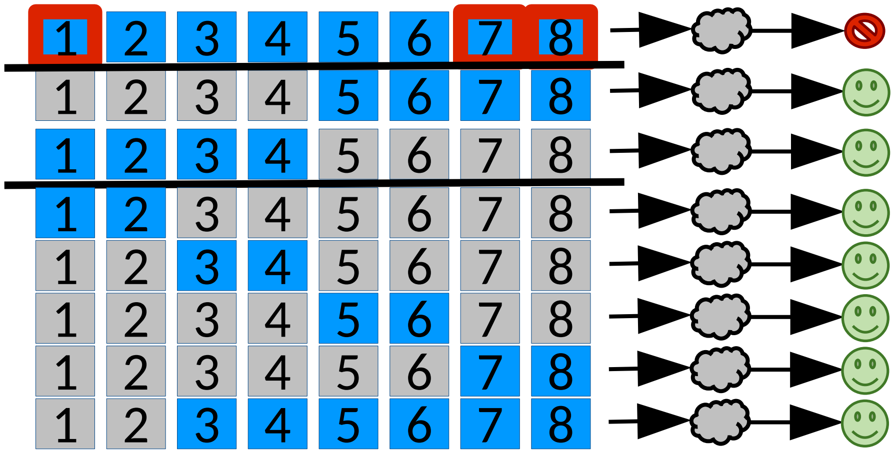


And now check complements

Classically – Delta Debugging



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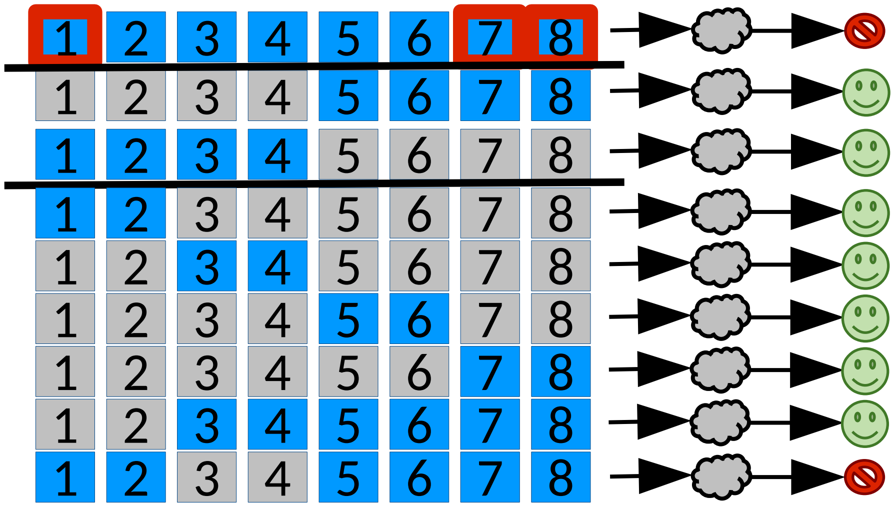

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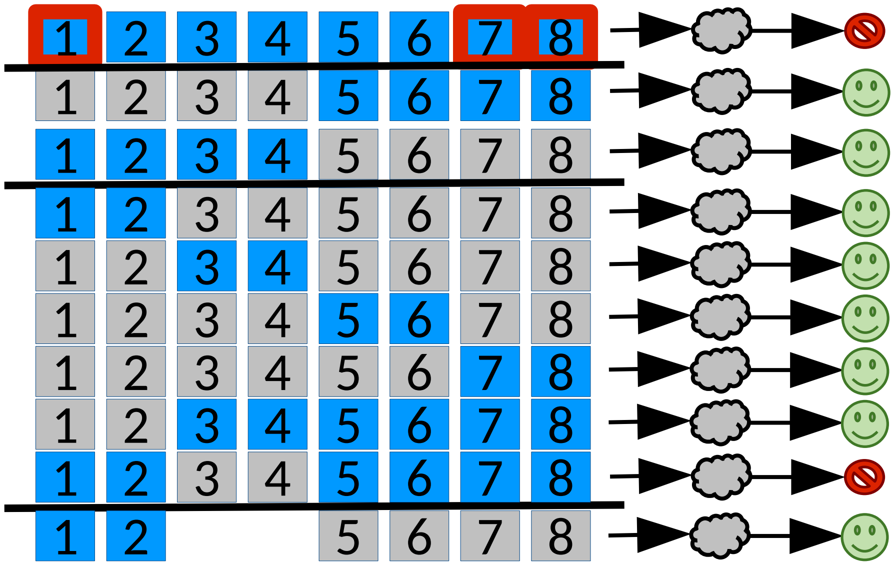

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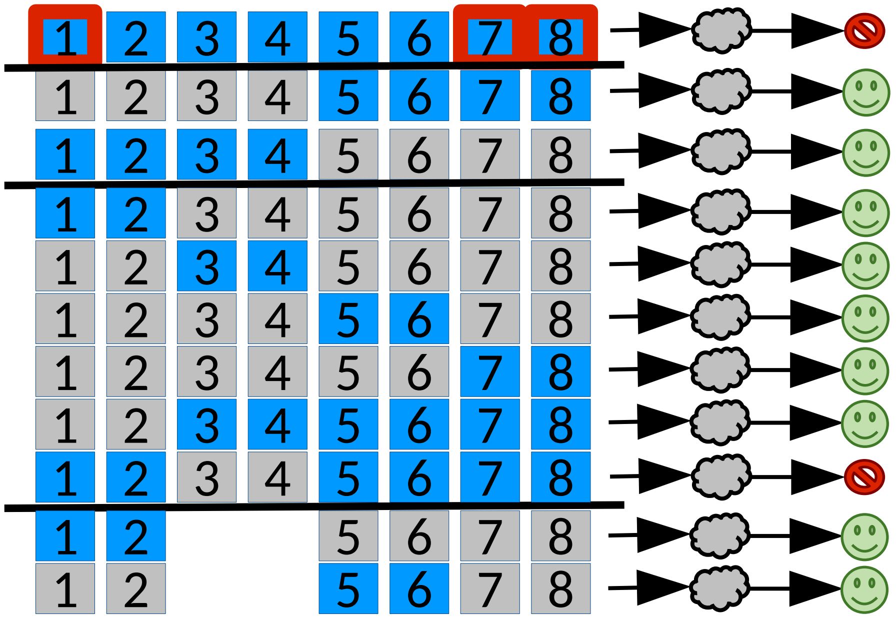

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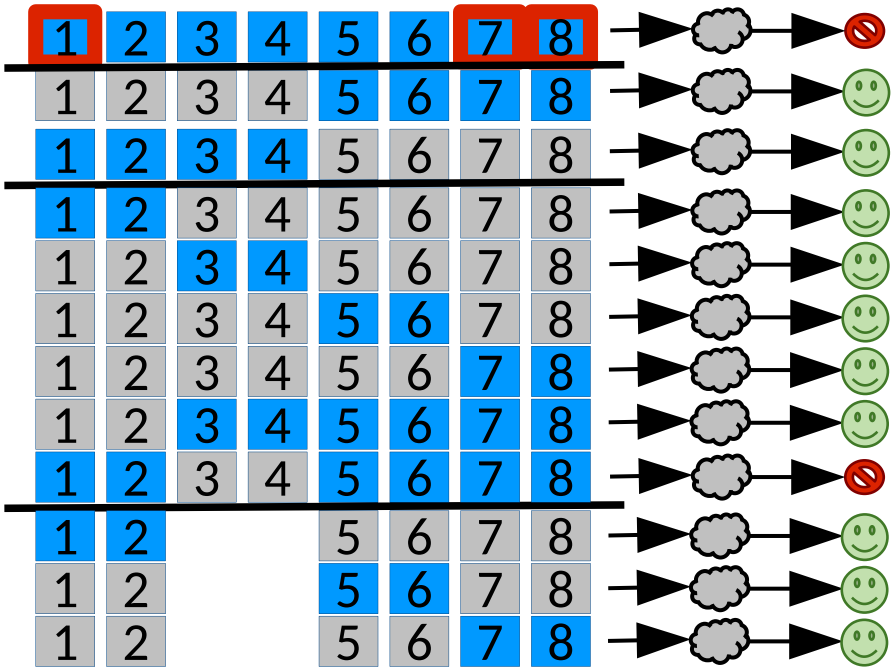
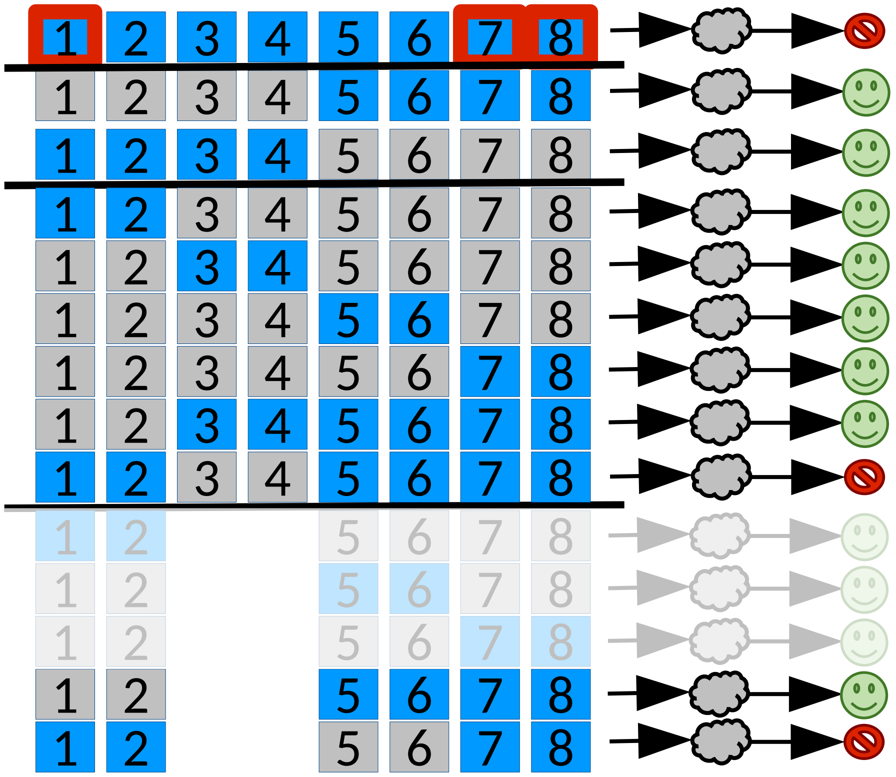


What's clever about how we recurse?

Classically – Delta Debugging



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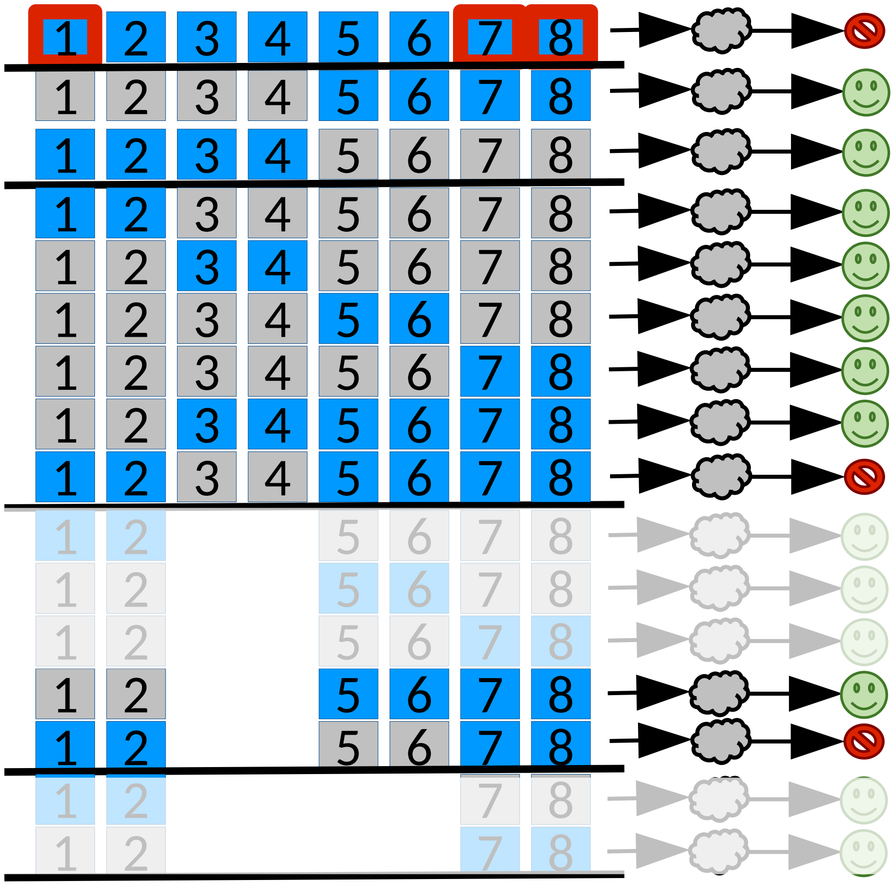
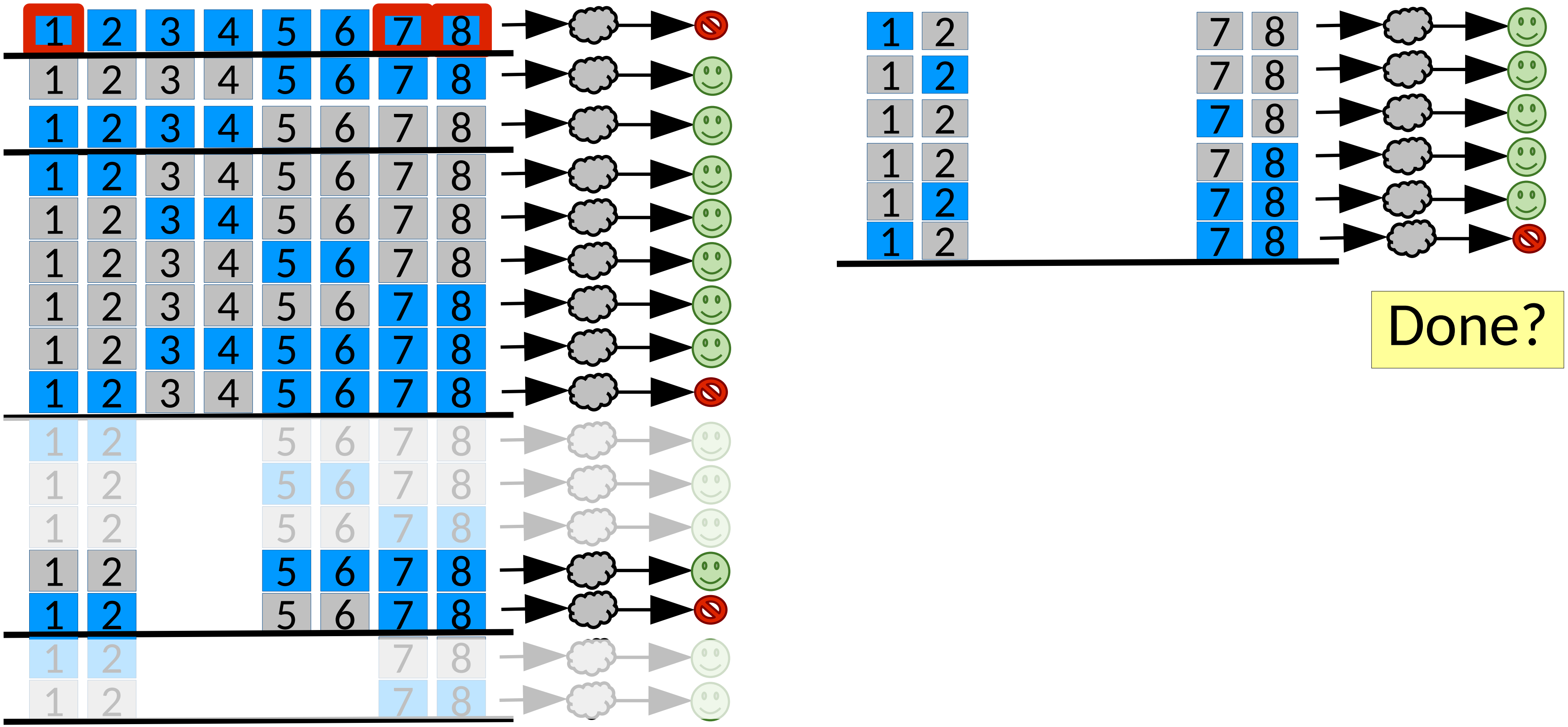


So close! How many more?

Classically – Delta Debugging



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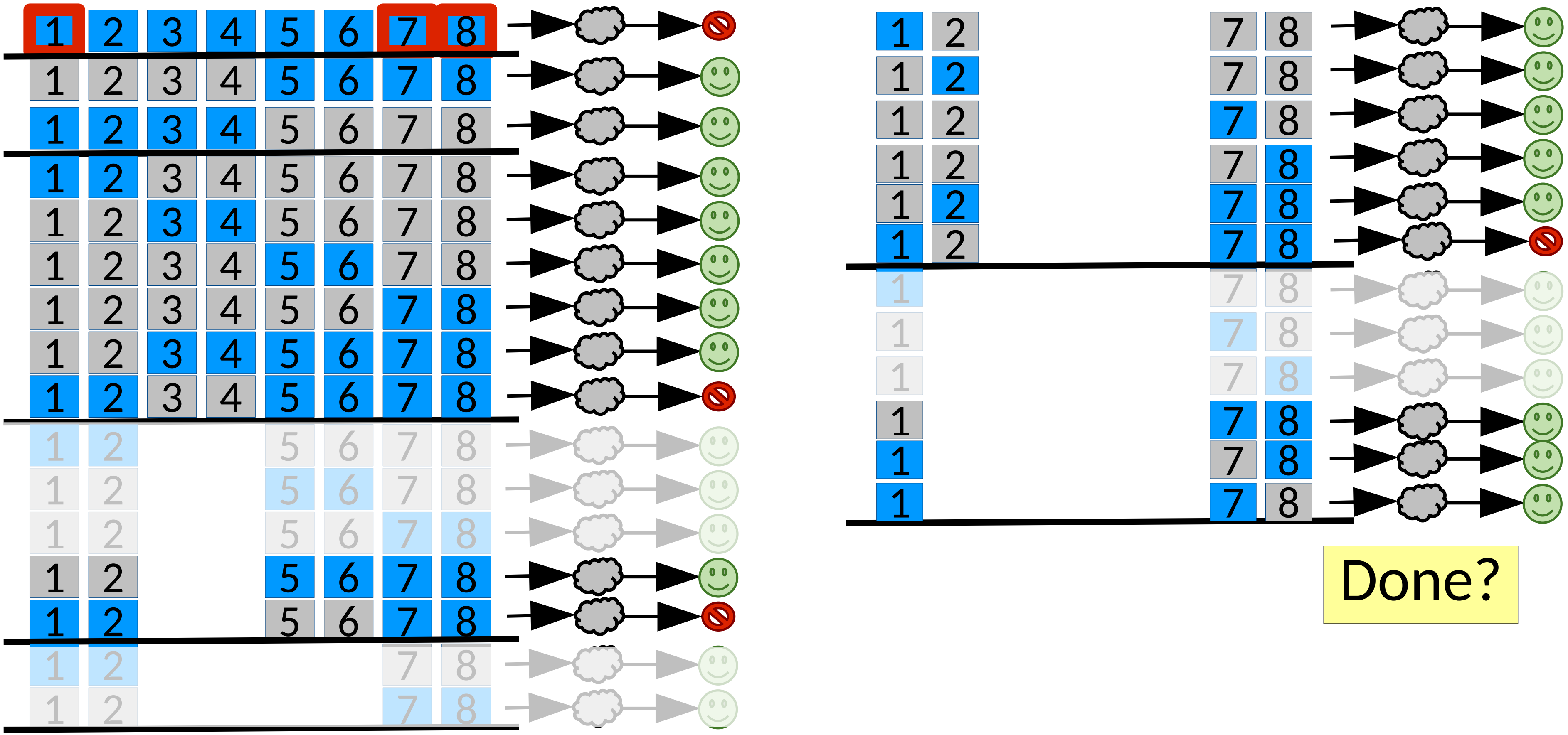


Classically – Delta Debugging

$ddmin(c) = ddmin_2(c, 2)$

Defined over
c - the input / configuration
n - the # of partitions

Classically – Delta Debugging

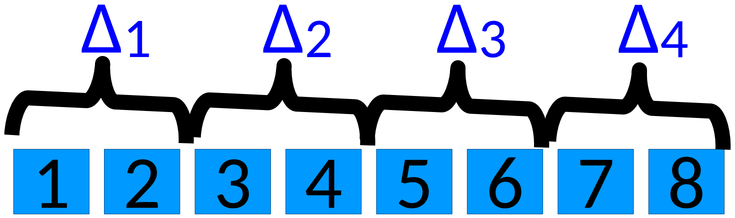
ddmin(c) = $ddmin_2$(c, 2)

c = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

Classically – Delta Debugging

ddmin(**c**) = ddmin$_2$(**c**, **2**)

c =



n = 4

Classically – Delta Debugging

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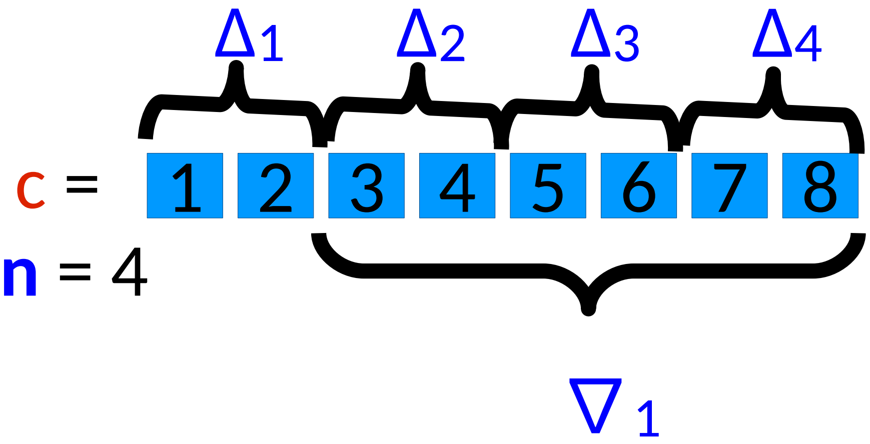


Classically – Delta Debugging

$\text{ddmin}(c) = \text{ddmin}_2(c, 2)$

$$\text{ddmin}_2(c, n) = \begin{cases} \\ \\ \end{cases}$$

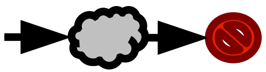
Classically – Delta Debugging

$ddmin(\textbf{c}) = ddmin_2(\textbf{c}, \textbf{2})$

$$ddmin_2(\textbf{c},\textbf{n}) = \begin{cases} ddmin_2(\Delta_i, 2) & \text{If ... (a)} \end{cases}$$

Try each partition

$\Delta_i = \{3,4\}$ (a) 1 2 3 4 5 6 7 8



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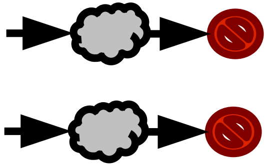
Try each complement

$\Delta_i = \{3,4\}$

(a)	1	2	3	4	5	6	7	8
(b)	1	2	3	4	5	6	7	8



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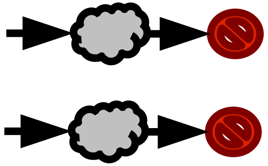

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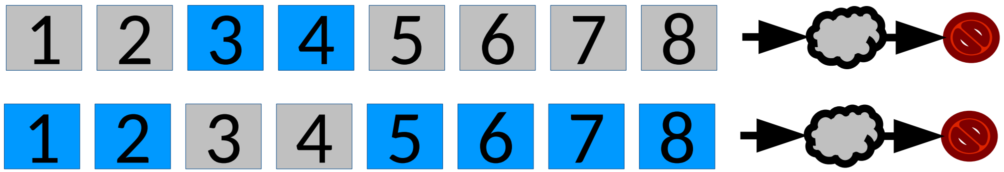
Refine the granularity

$\Delta_i = \{3,4\}$ (a)

(b)



(c) $n < |c|$

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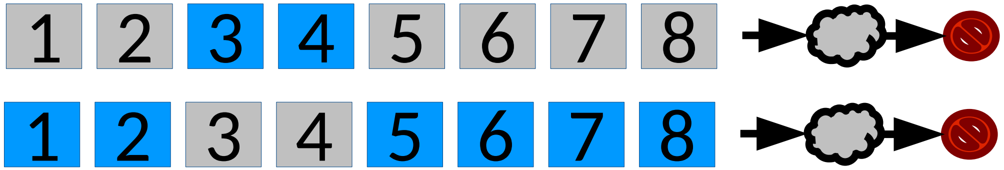

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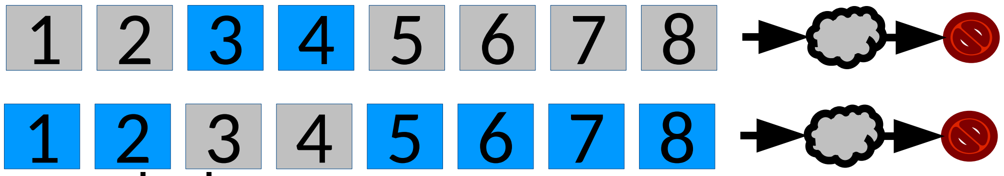
Finish

$\Delta_i = \{3,4\}$ (a)

(b)



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  - ***Does formal minimality even matter?***

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  In practice DD may revisit elements in order to guarantee minimality

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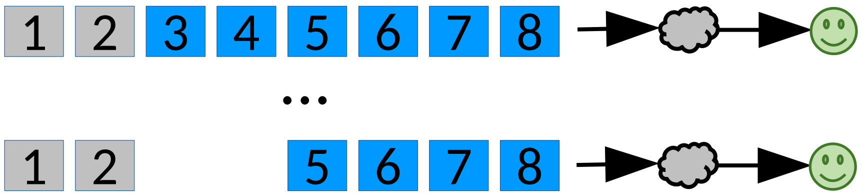
ddmin$_2$(∇**i**, **max(n-1,2)**)



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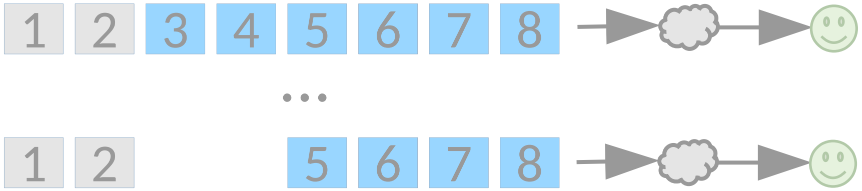

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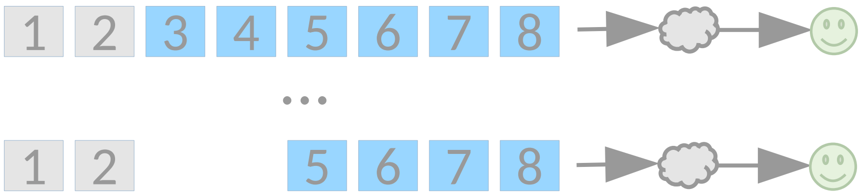

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Don’t get bogged down by formalism
when it doesn’t serve you!

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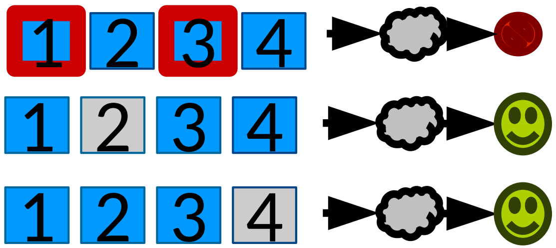

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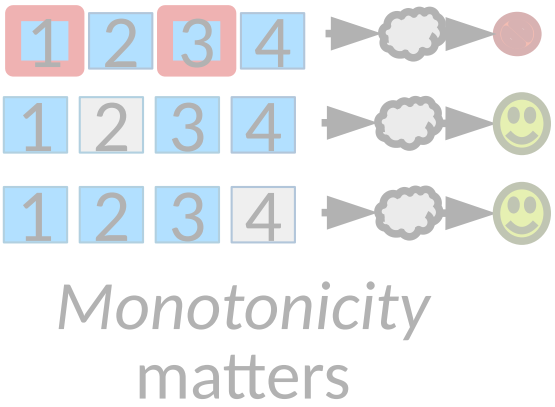

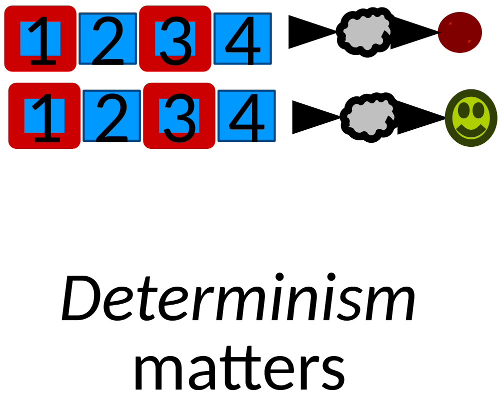

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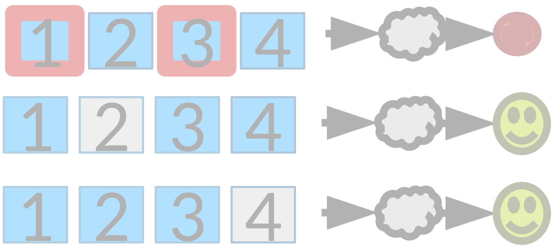

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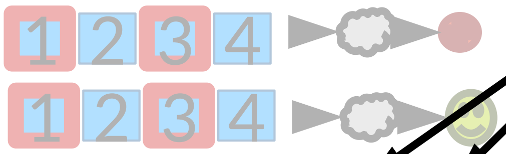
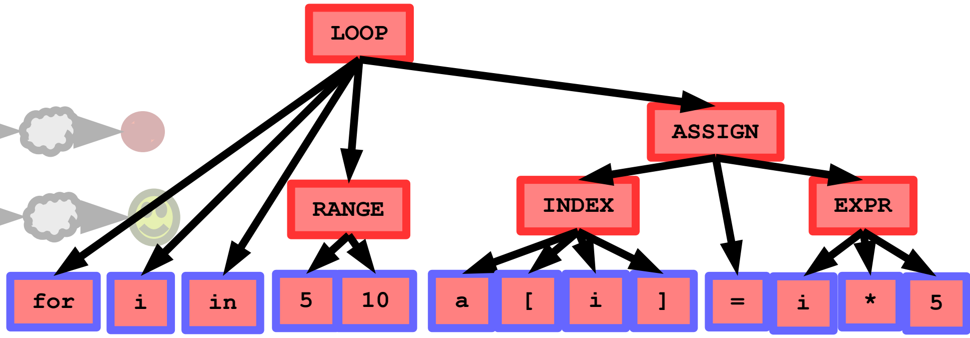


Determinism matters



Structure matters

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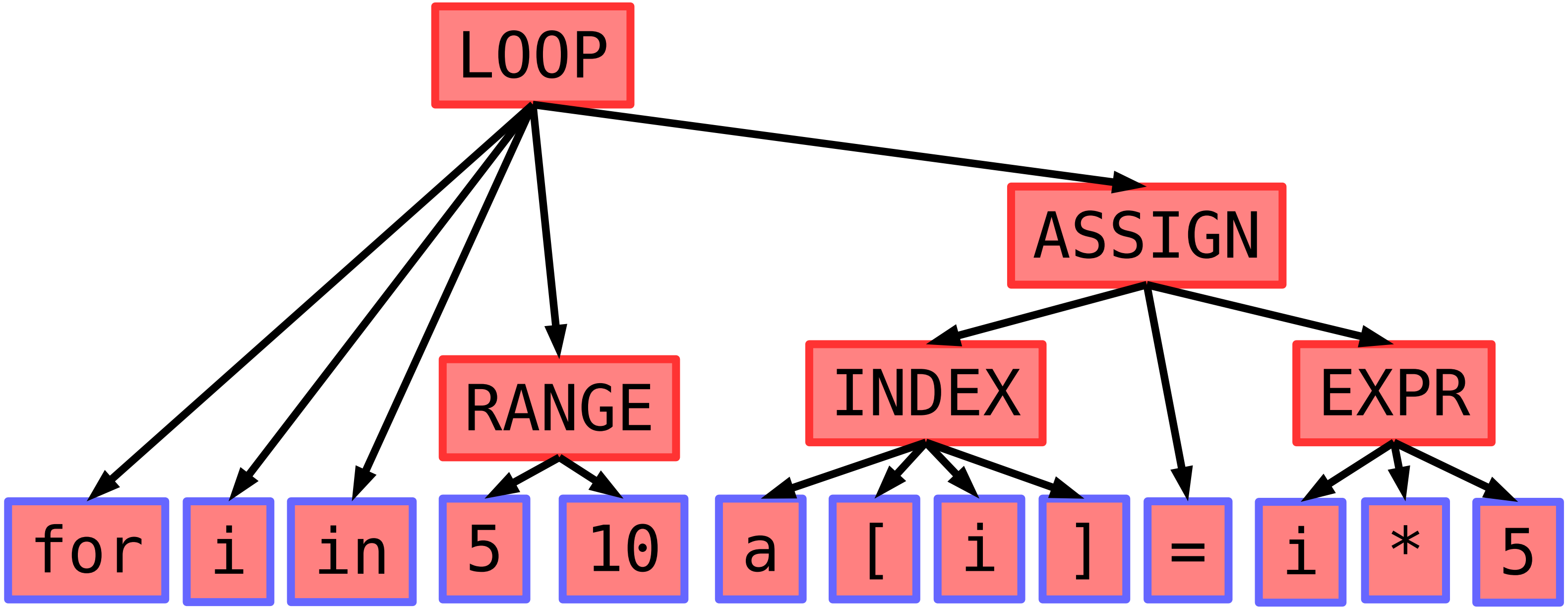
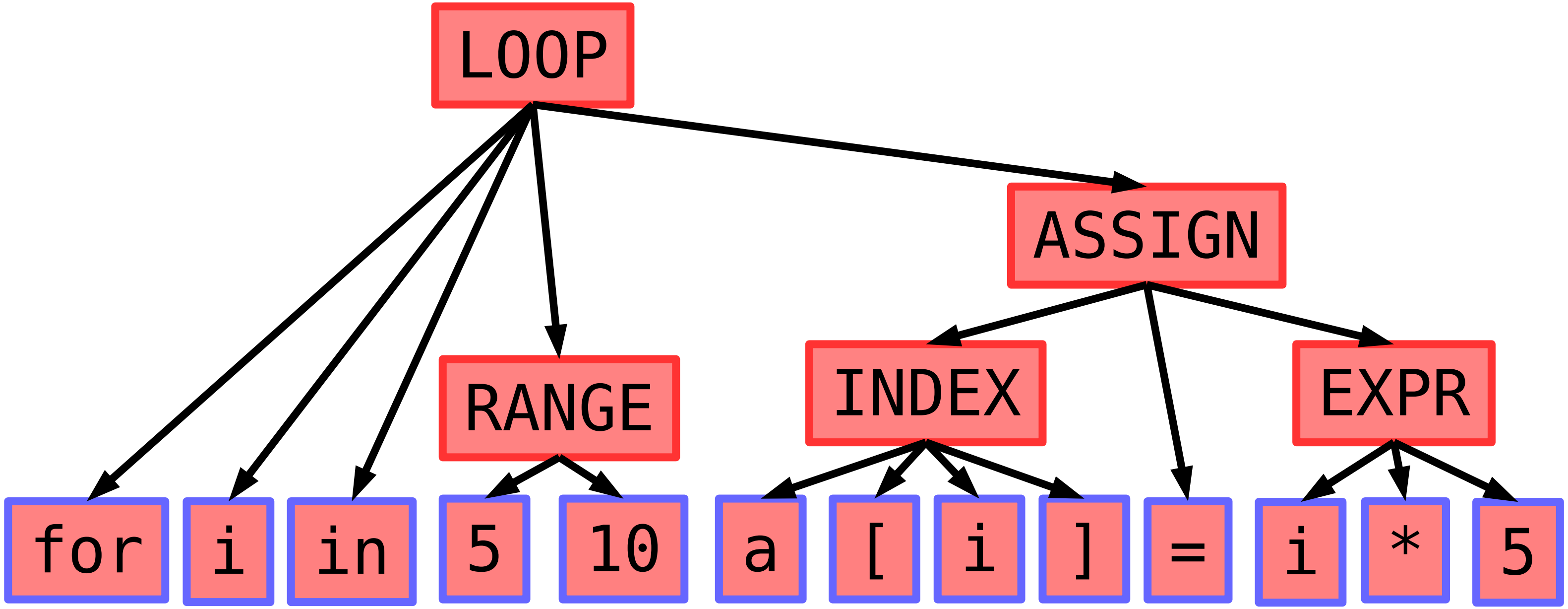


Test Case Reduction for Compilers

- Programs are highly structured, so TCR for compilers faces challenges
- What structures could we use to guide the process?
- What challenges still remain?



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  - We saw this before when discussing test suites!

Example: Memory Safety Bugs

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- Two main types of issues:
  - Spatial – Out of bounds stack/heap/global accesses
  - Temporal – Use after free
- We would like to automatically identify & provide assistance with high precision and low overhead
  - Suitable for testing & sometimes maybe deployment!

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Note, the implementation style affects
which bugs can be recognized!
Why?

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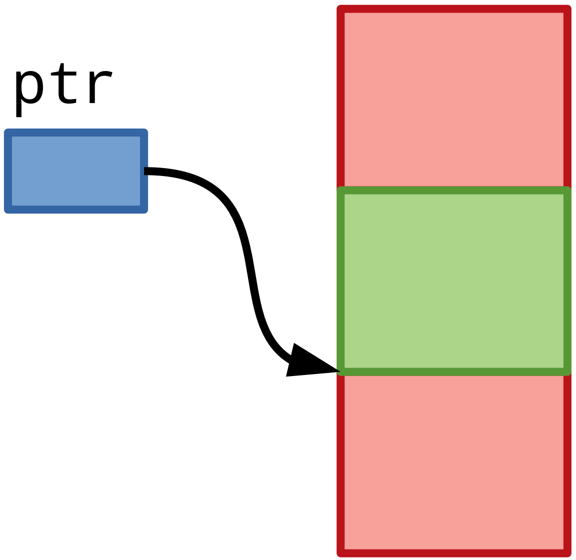


```
ptr = malloc(sizeof(MyStruct));
```

AddressSanitizer

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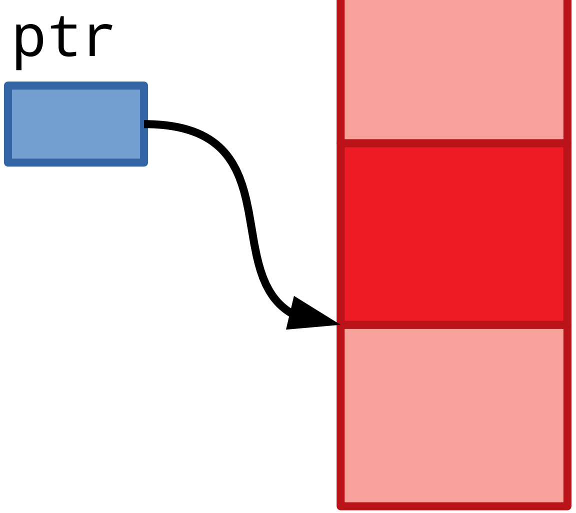
    1) around `malloc`ed chunks
    2) when it is `free`d




```
free(ptr);
```

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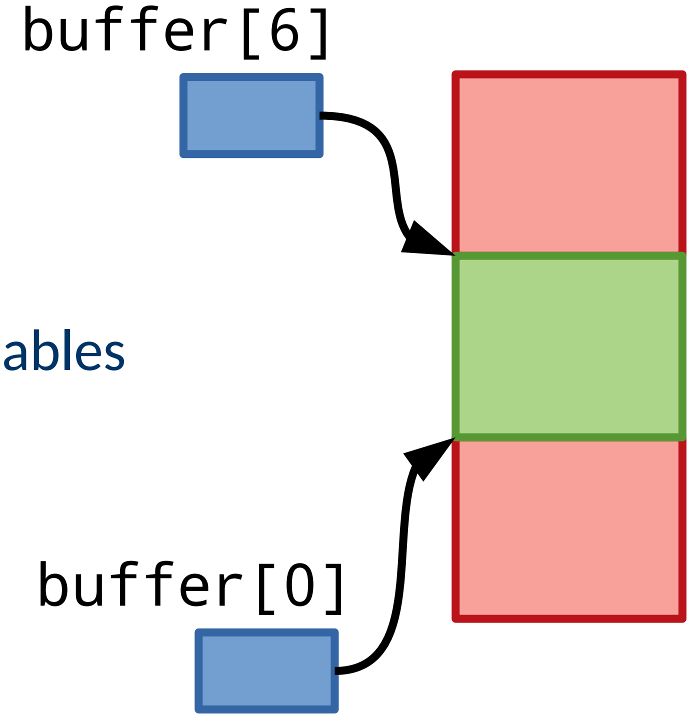
    1) around `malloced` chunks
    2) when it is `freed`
    3) around buffers and local variables

```
void foo() {
  int buffer[5];
  ...
}
```



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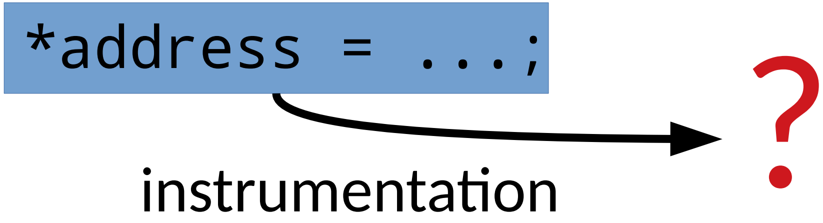

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```
*address = ...;
```

instrumentation →

```
If (IsPoisoned(address, size)) {
  ReportError(address, size, isWrite);
}
*address = ...
```

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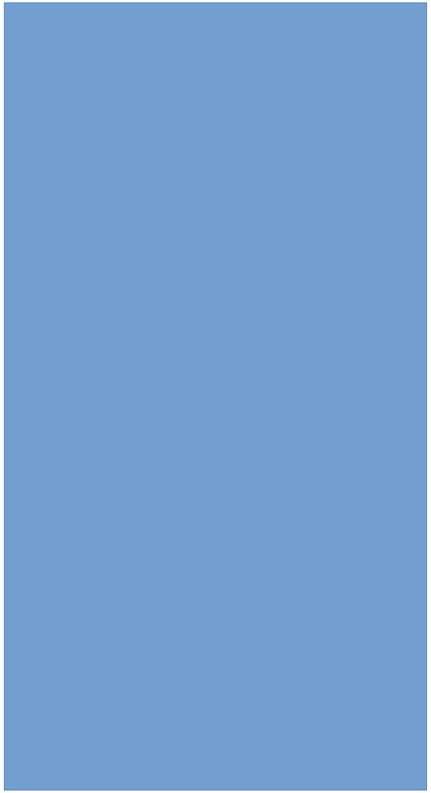
This kind of issue is common in dynamic analyses.

AddressSanitizer – Shadow Memory

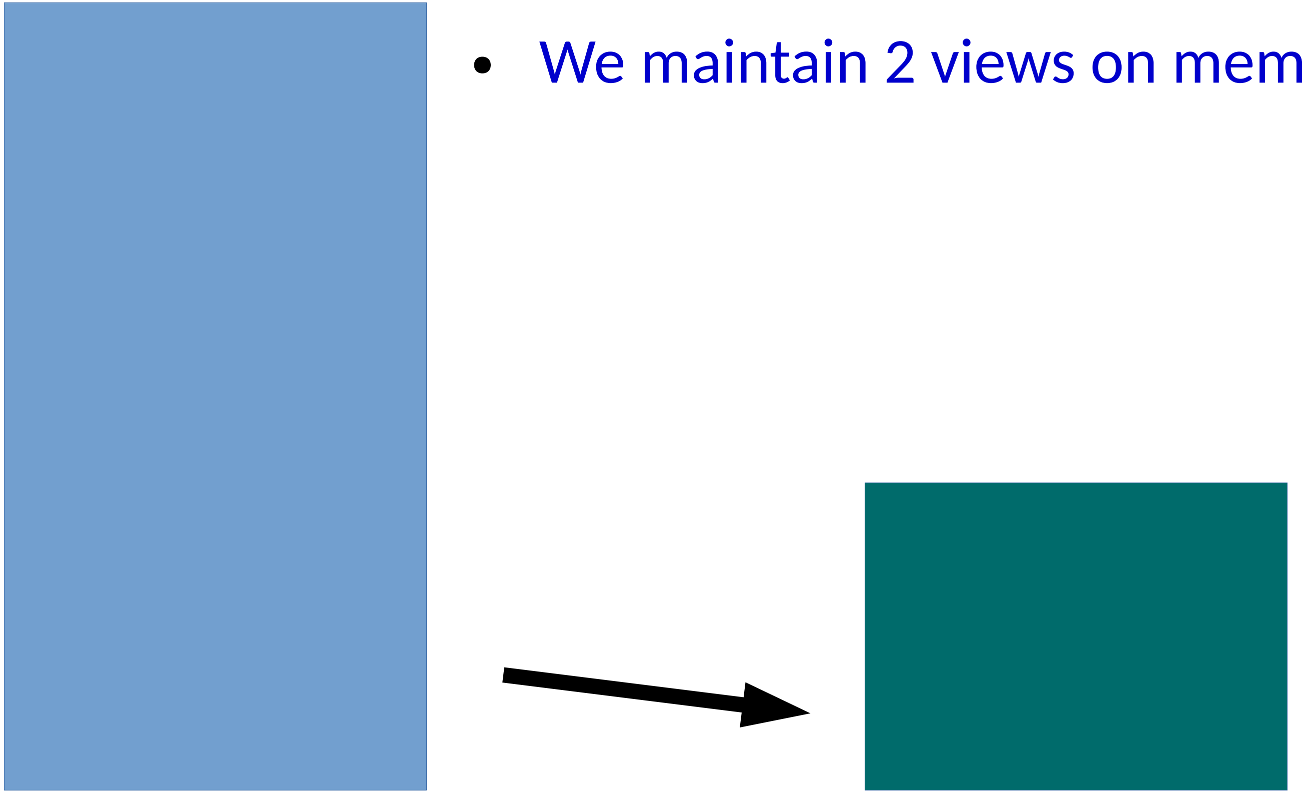


Application Memory

Need to know whether *any byte* of application memory is poisoned.

AddressSanitizer – Shadow Memory

- We maintain 2 views on memory



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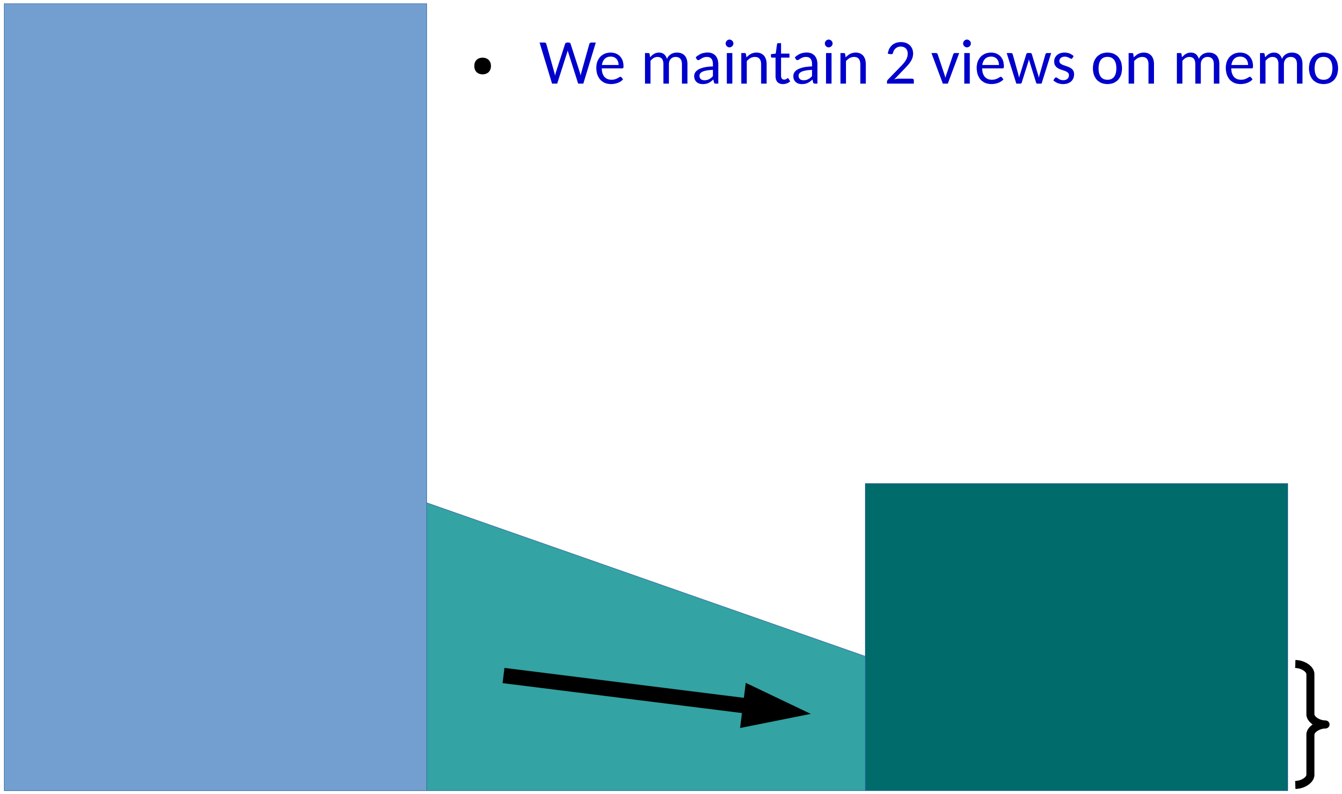

Shadow memory of the shadow memory!

Application Memory *Shadow* Memory

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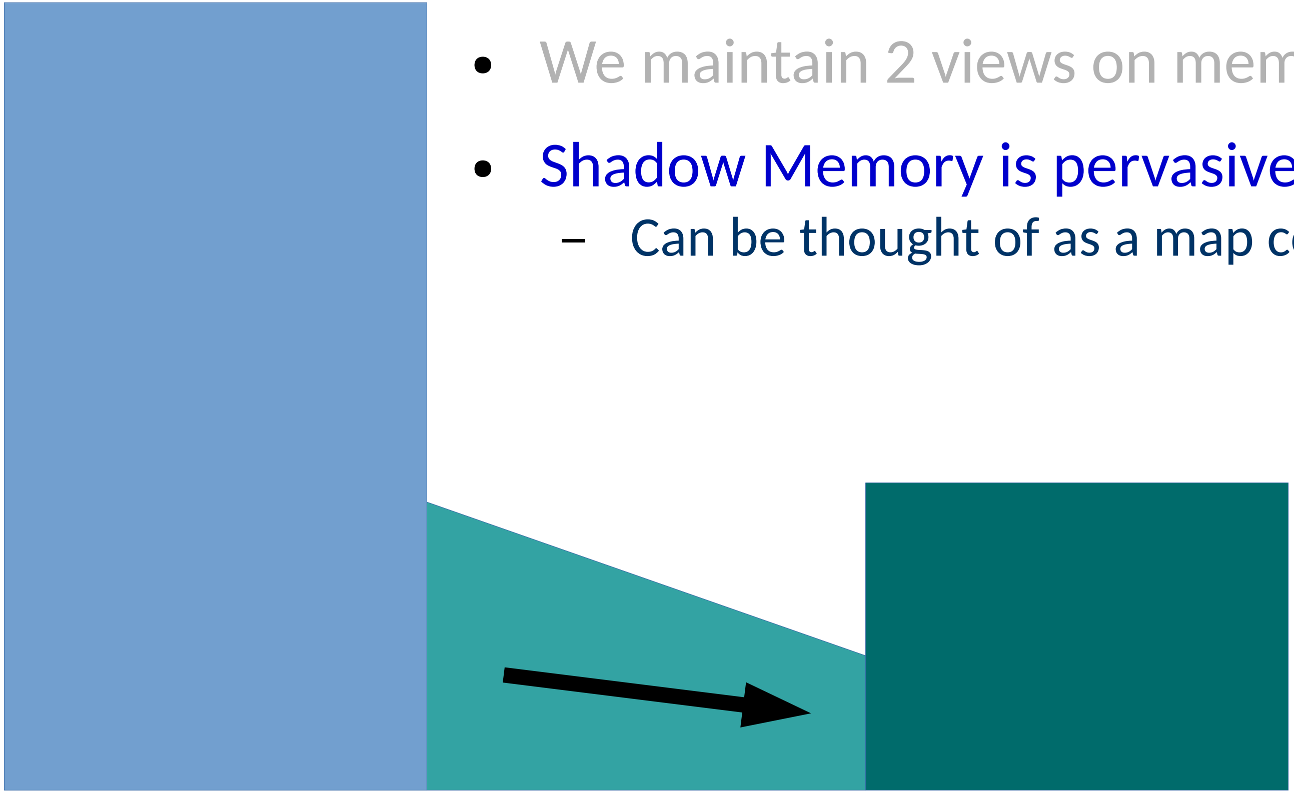
  - Can be thought of as a map containing analysis data



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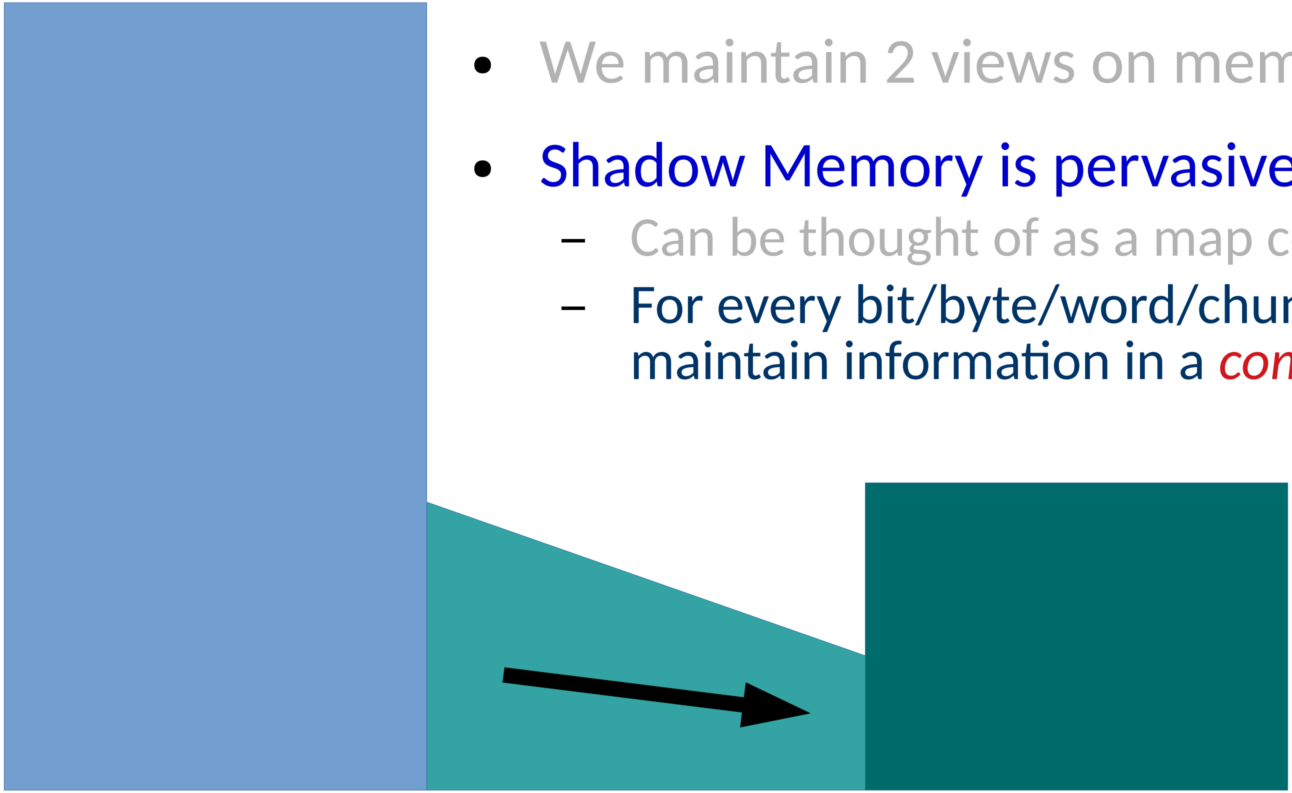

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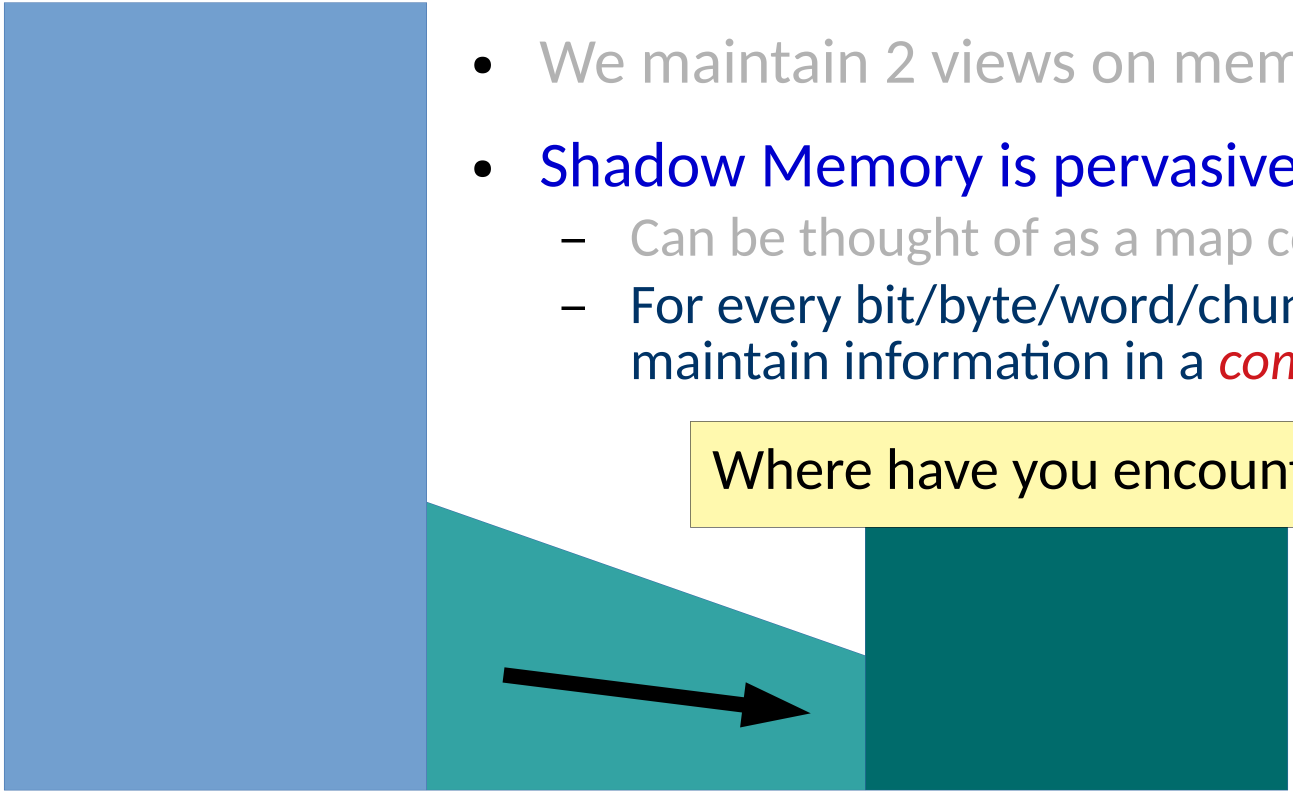
Where have you encountered this before?



Application Memory

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AddressSanitizer – Shadow Memory

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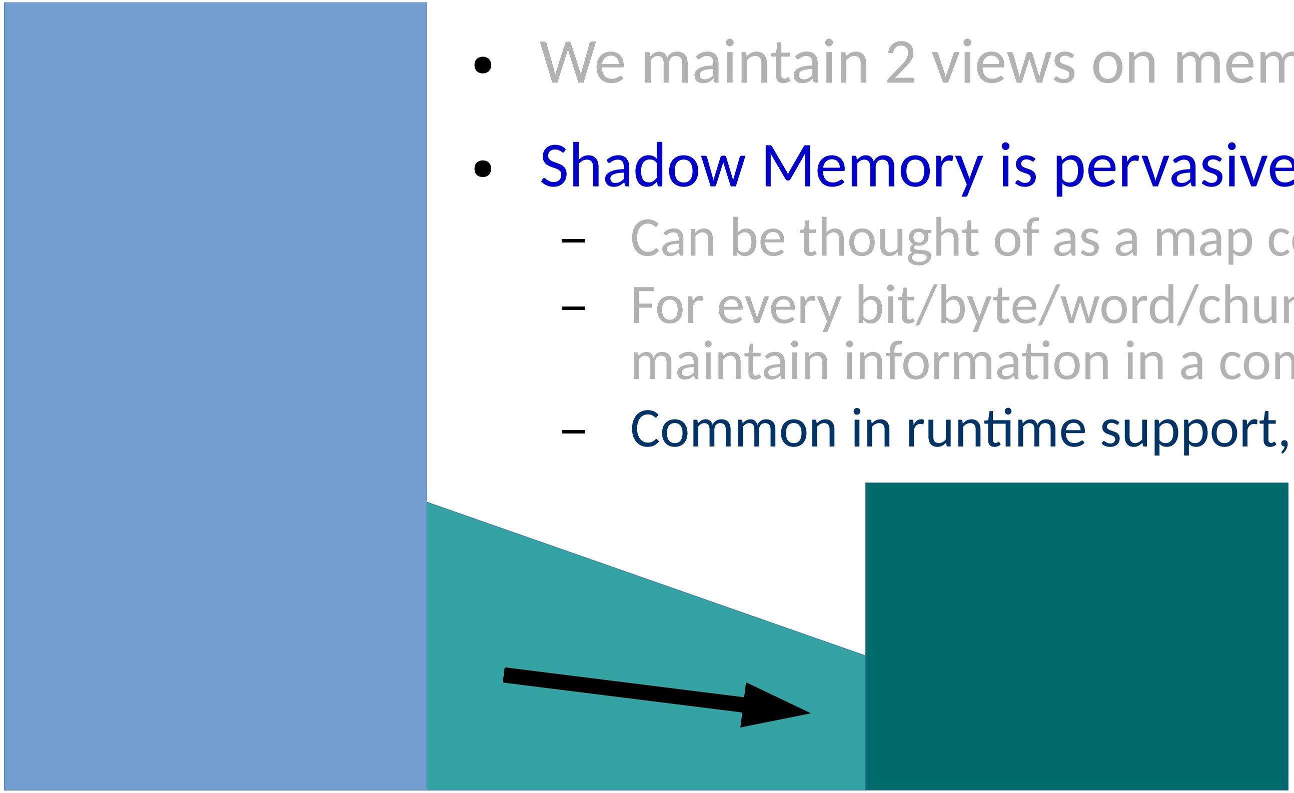
  - Common in runtime support, e.g. page tables



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AddressSanitizer – Shadow Memory

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Encoding & abstraction
efficiency strategies

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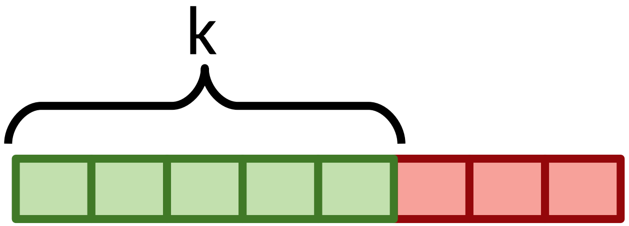

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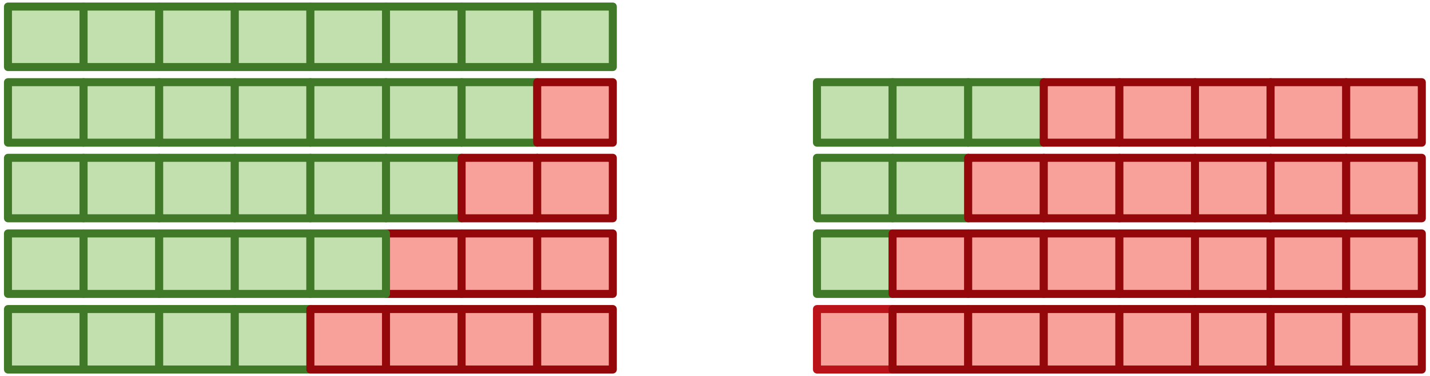

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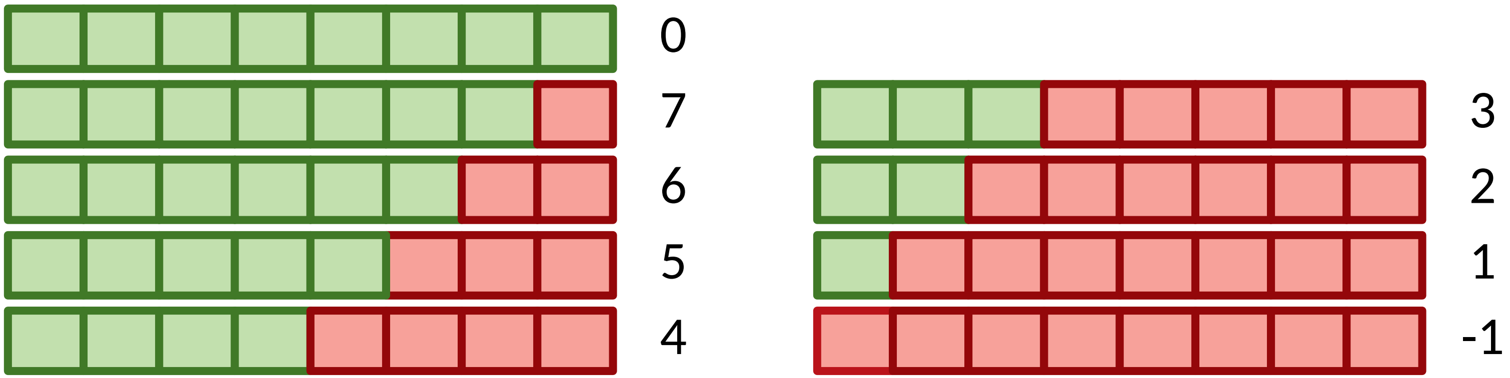

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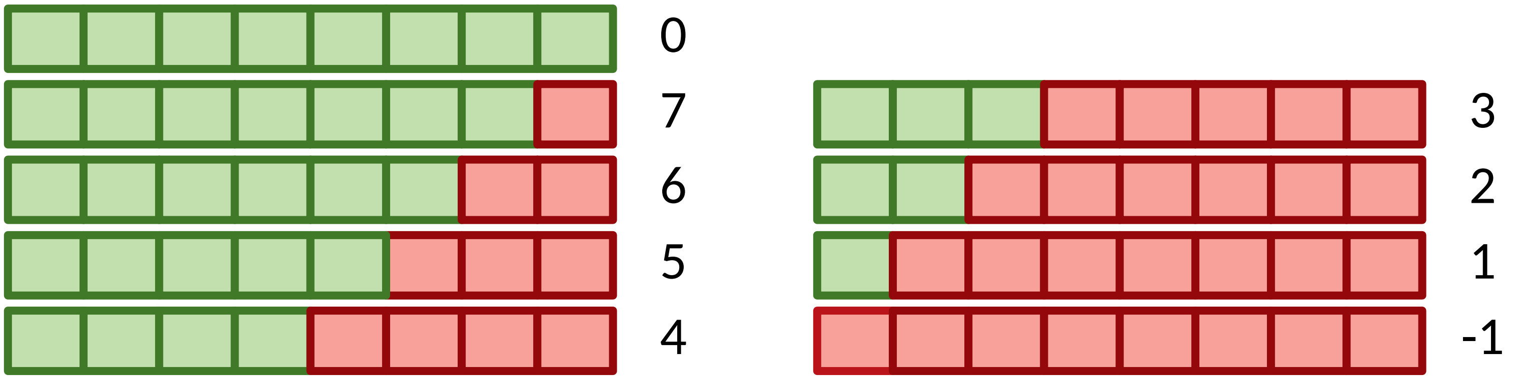

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if (*(address>>3)) {
  ReportError(...);
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Now you can also see the reason for the numerical encoding....

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AddressSanitizer – Shadow Memory

- Handling accesses of size < N (N=8)

```
shadow = address >> 3
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Careful construction of states can make runtime checks efficient

AddressSanitizer - Evaluating

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    Can effectively be free for I/O bound projects
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- Quality
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Where will it miss bugs?
Where will it raise false alarms?

AddressSanitizer - Evaluating

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  - Use after frees with significant churn

Example: Comparing Executions

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- Understanding the differences between two executions
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  - Reverse engineering – desired behavior vs undesirable

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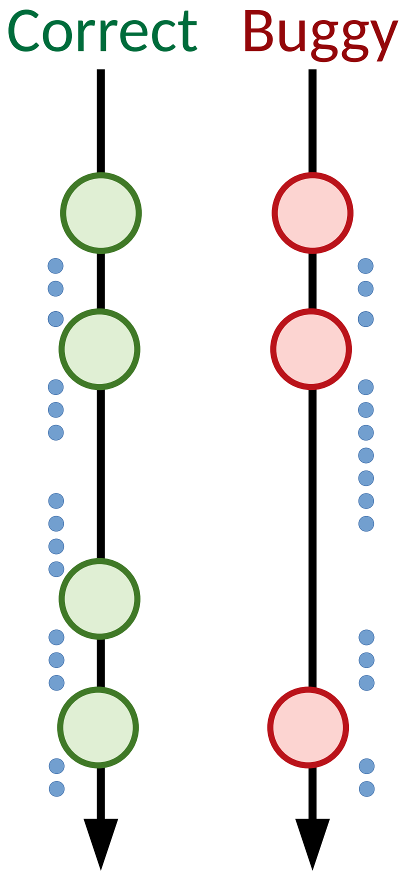

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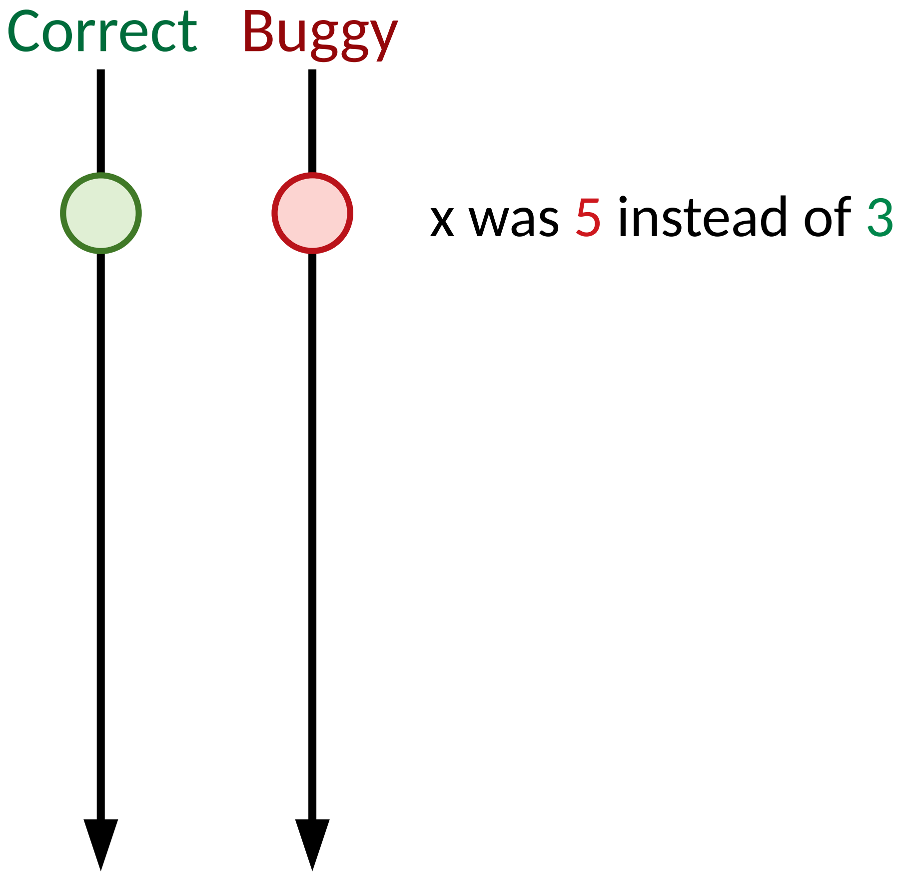

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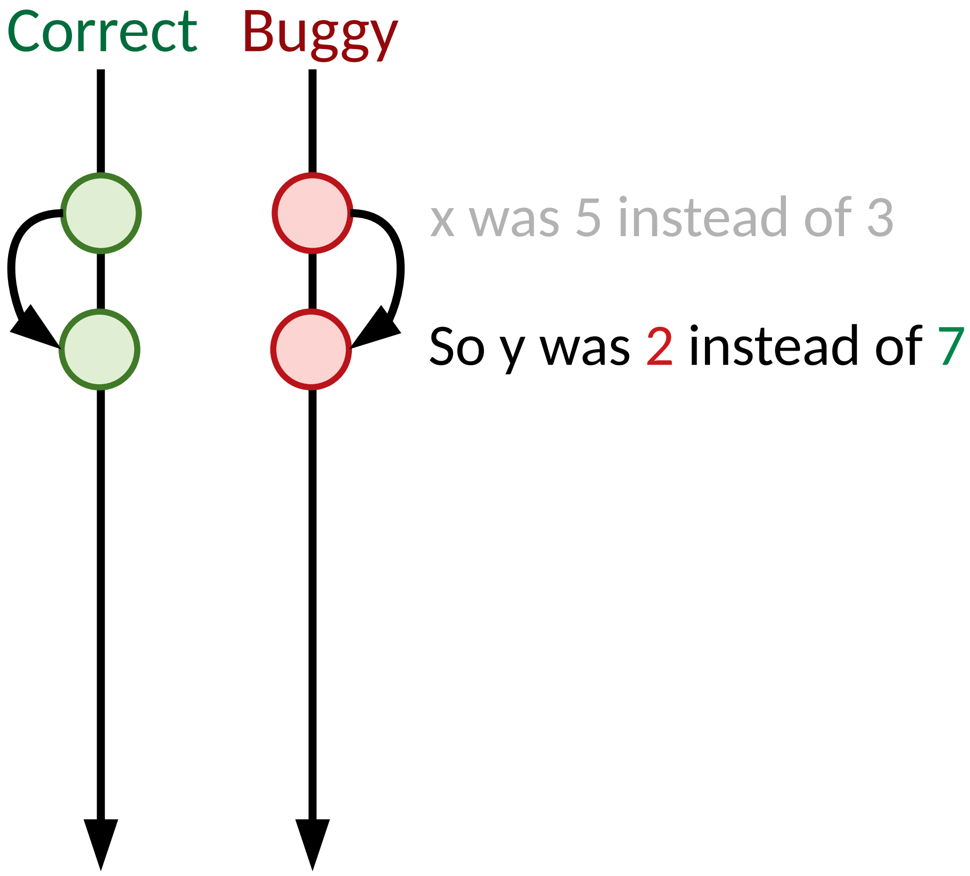

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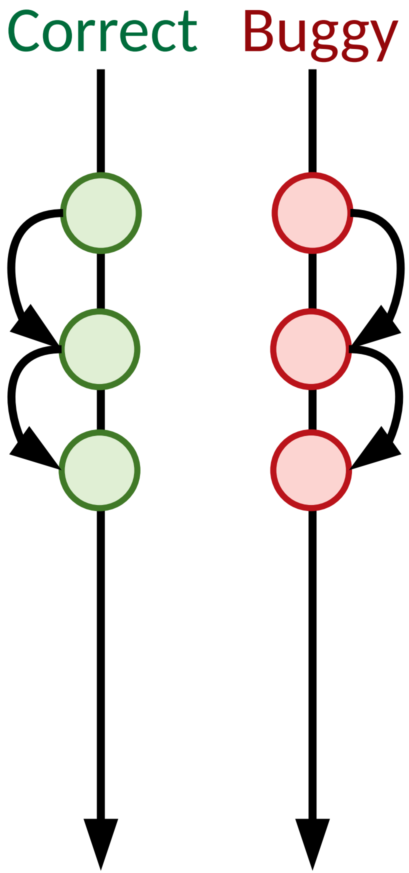

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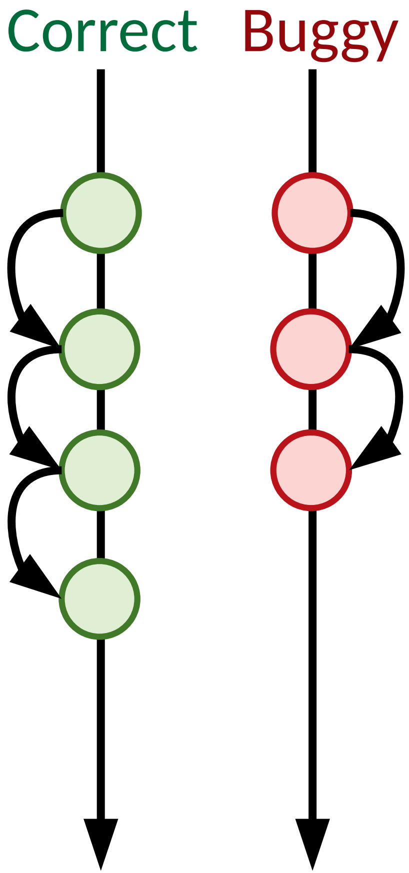

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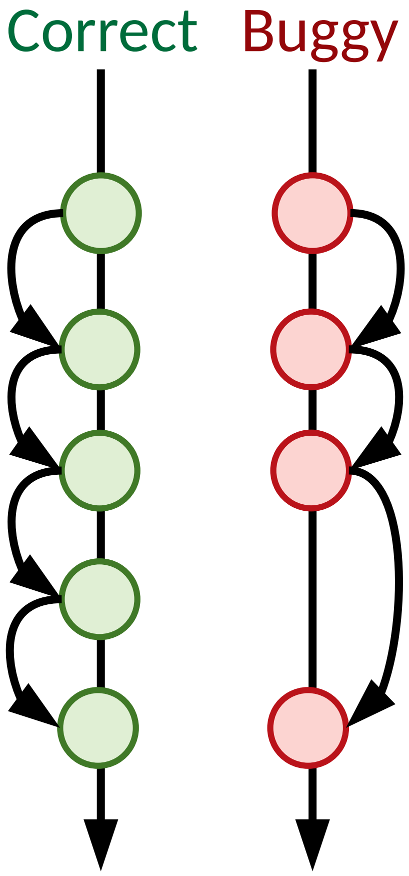

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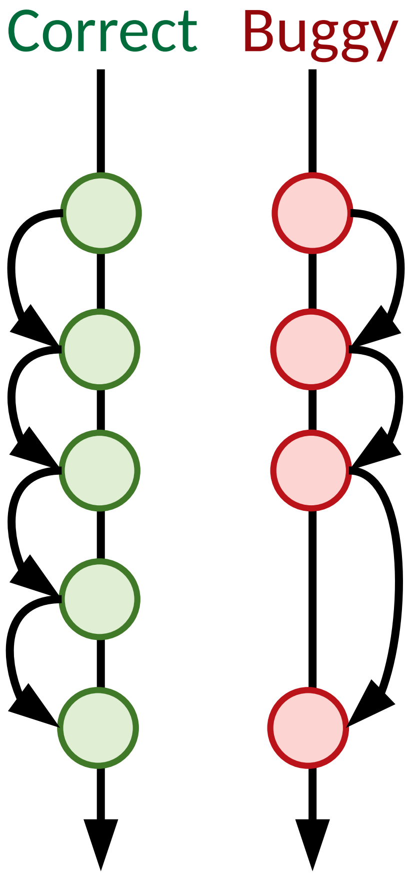

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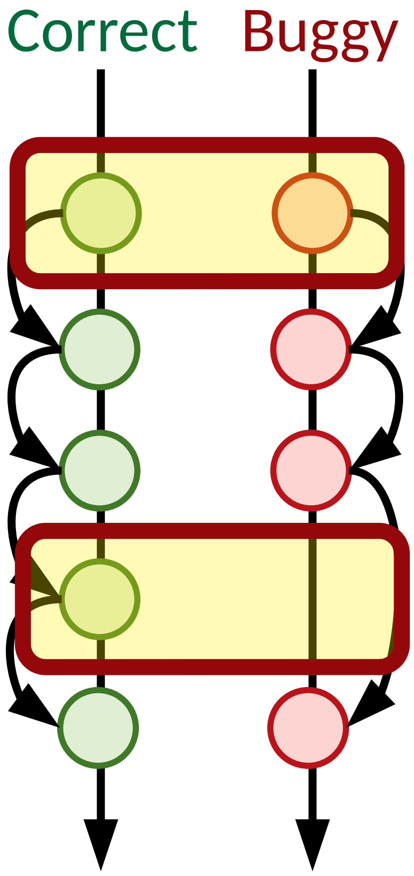

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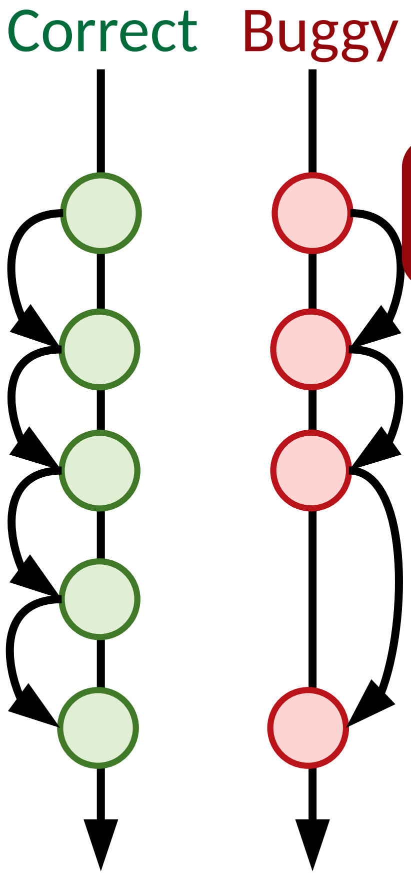

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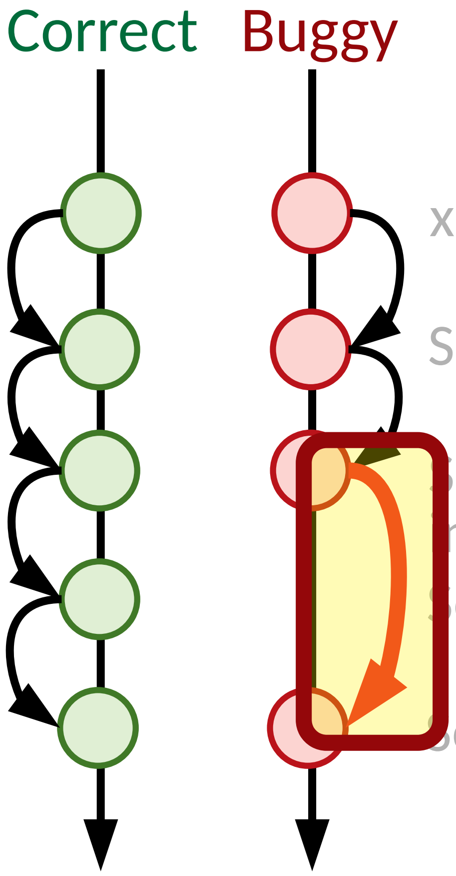

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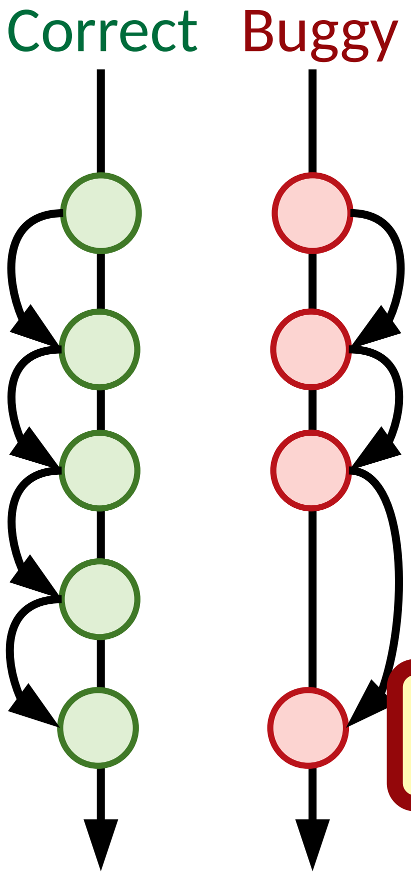

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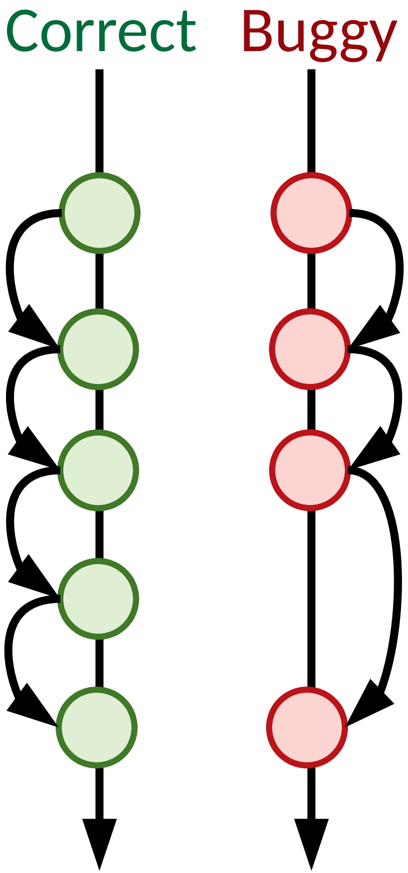

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We can construct this backward from a point of failure/difference

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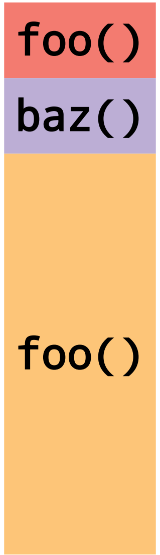

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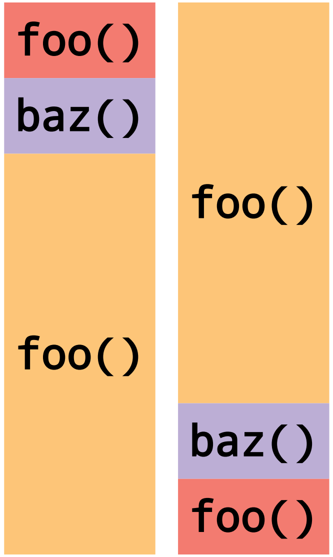

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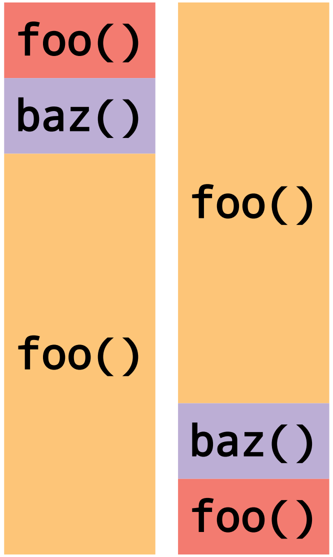

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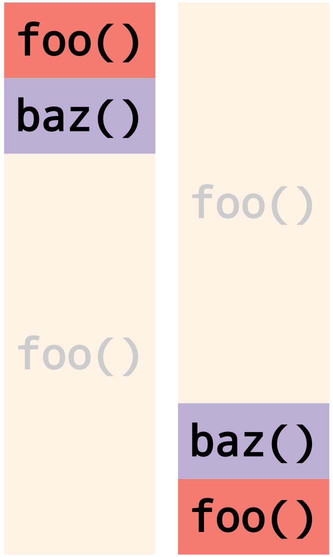

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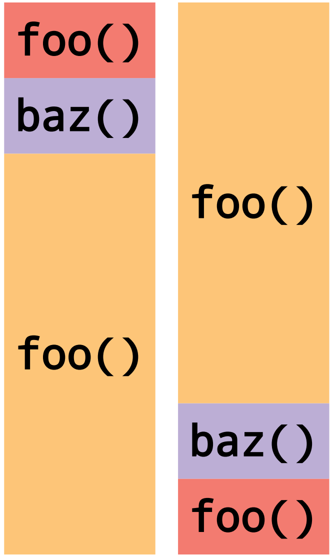

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What is *intuitively* different?

So why not just...

- Traces can be viewed as sequences....
  - Why not just do LCS based sequence alignment?

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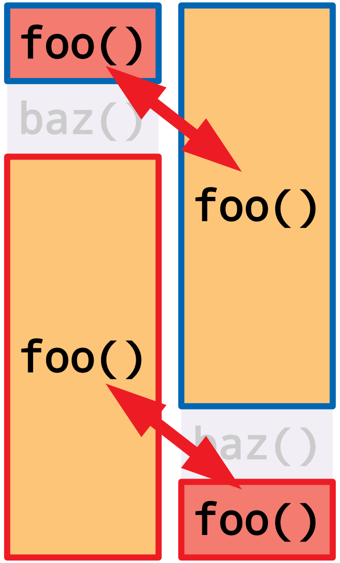
def foo(int c):
  if c:
    while bar():
      ...

foo(...)
baz(...)
foo(...)
```



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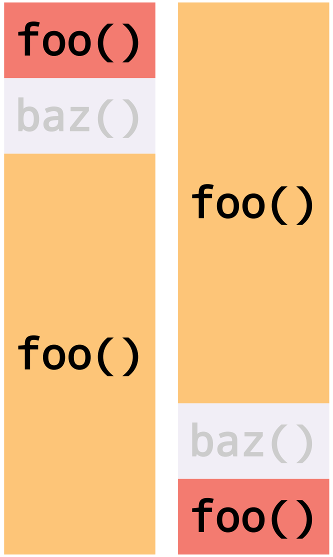

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Execution comparison must account for what a program *means* and *does*!

The big picture

- Fundamentally, execution comparison needs to account for

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  - Structure – How is a program organized?
  - Value – What are the values in the different executions?
  - Semantics – How is the meaning of the program affected by the differences?

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  - Value
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    - What parts of the trace correspond?
  - Spatial alignment
    - What variables & values correspond across traces?
  - Slicing
    - How do differences transitively flow through a program?
  - Causality testing
    - Which differences actually induce difference behavior?

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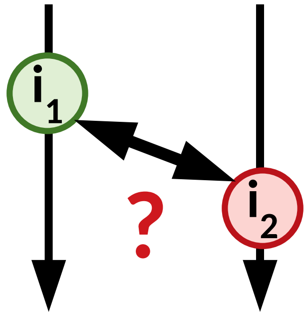

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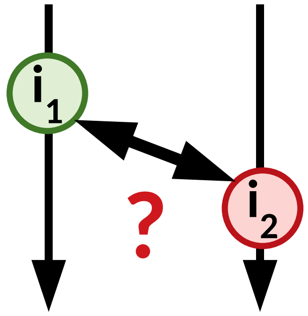

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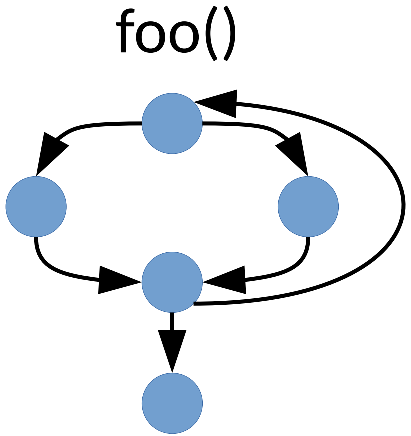

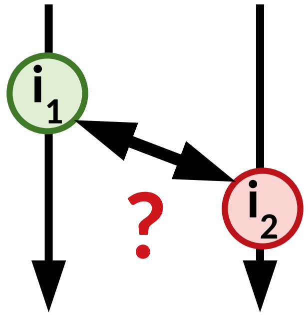

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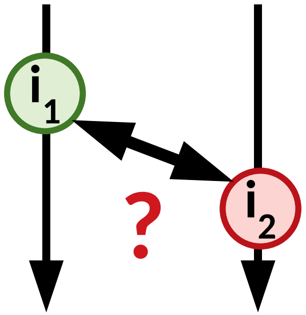

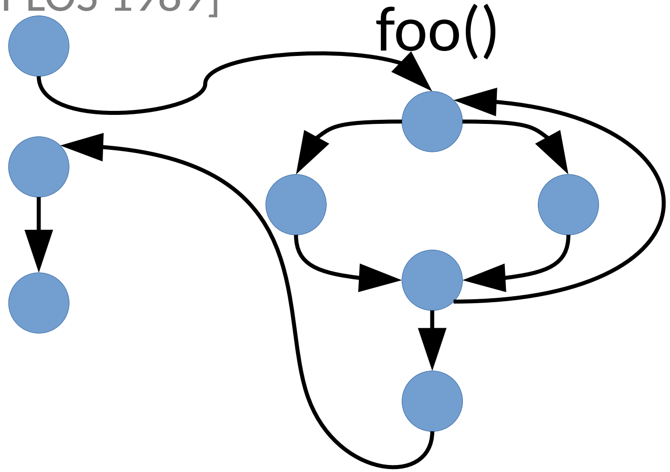

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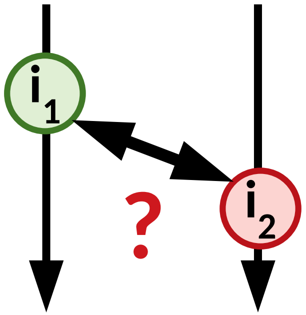

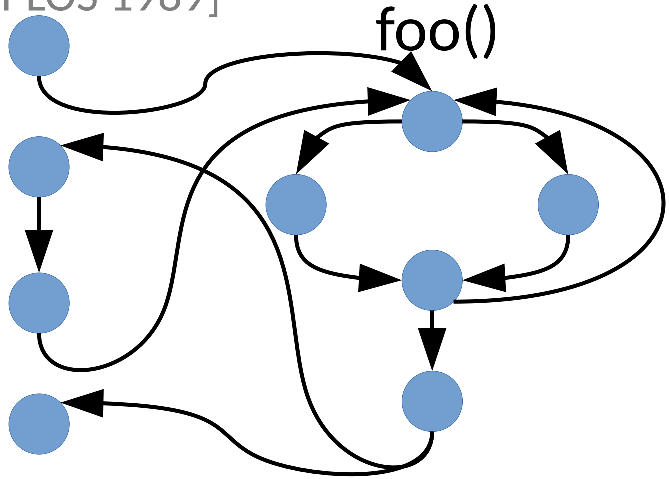

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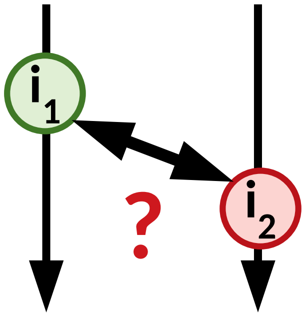

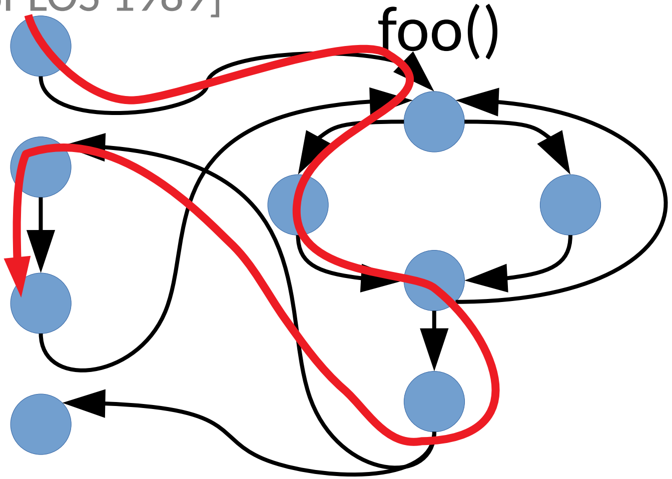

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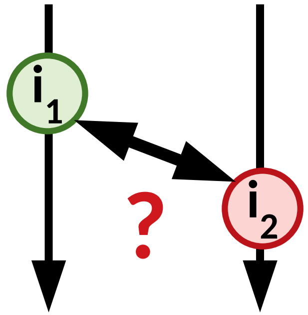

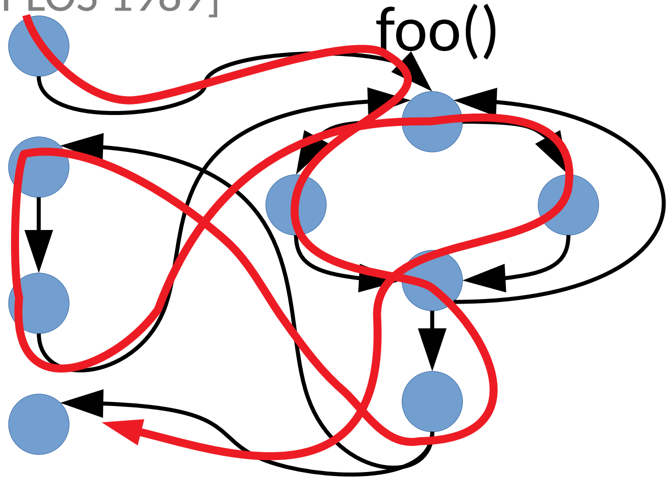

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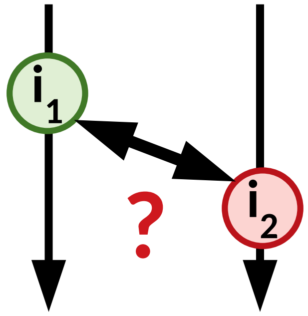

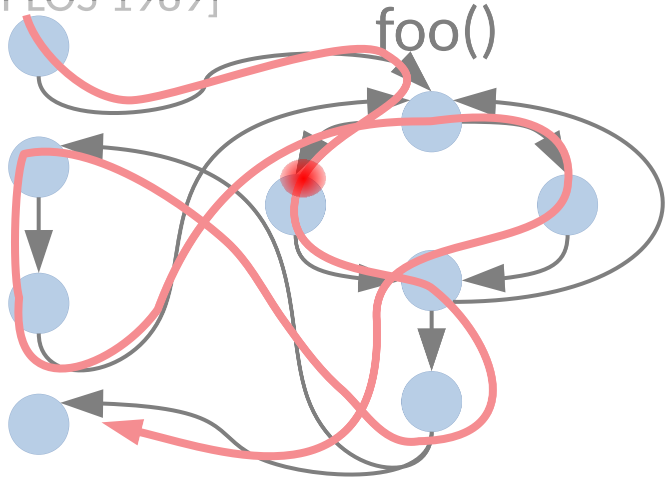

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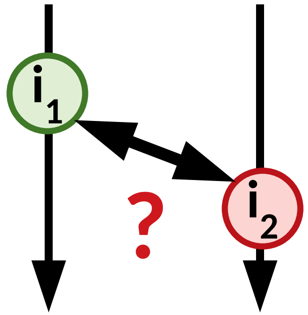

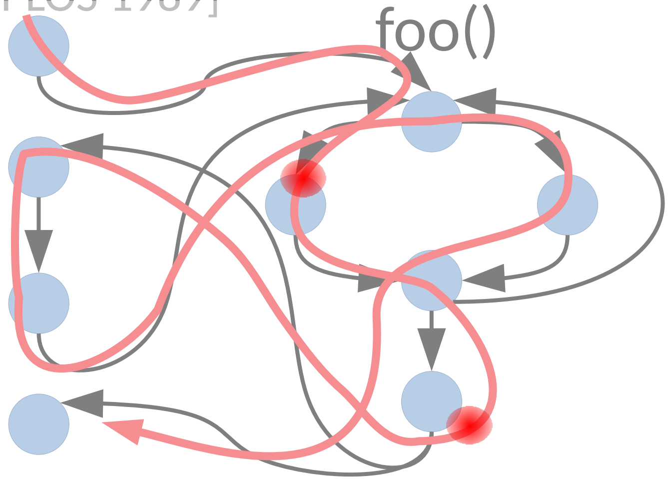

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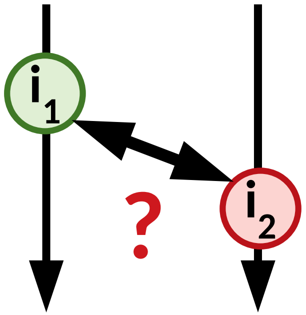

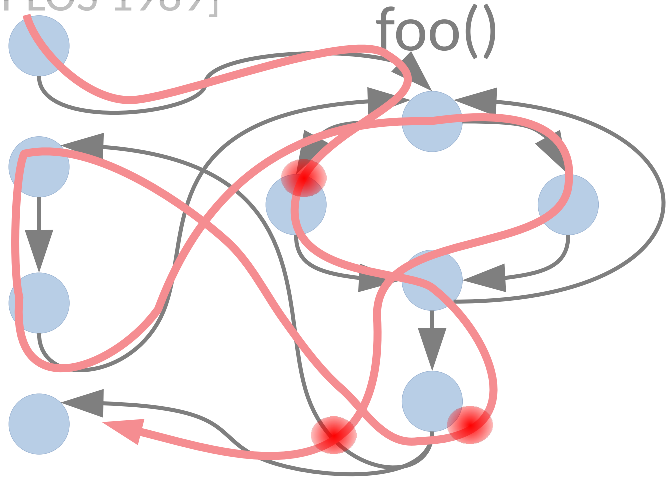

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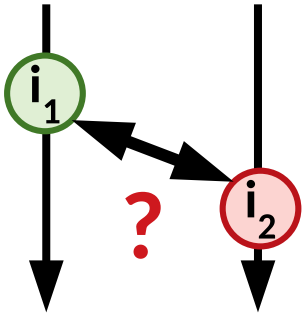

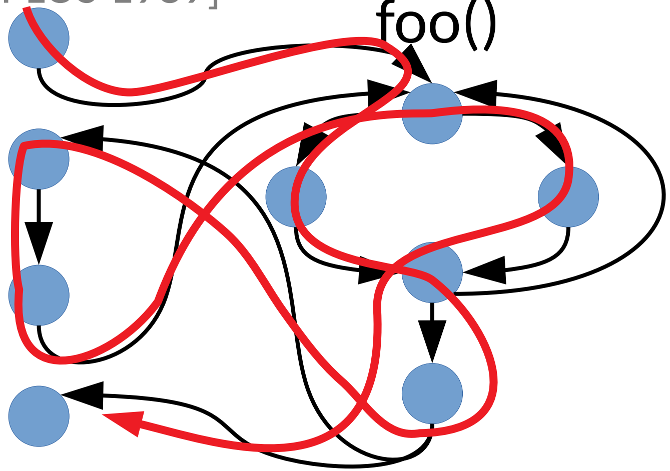

Position along a path can be maintained via a counter

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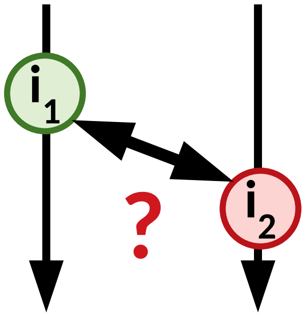

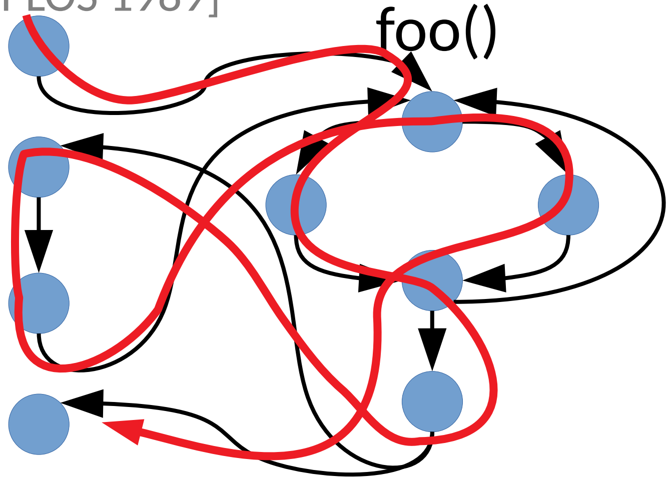

Position along a path can be maintained via a counter

Only need to increment along
1) back edges
2) function calls

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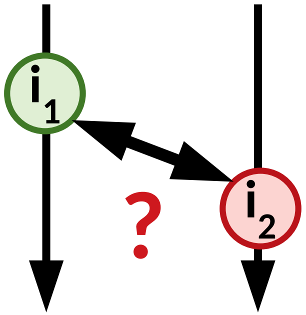

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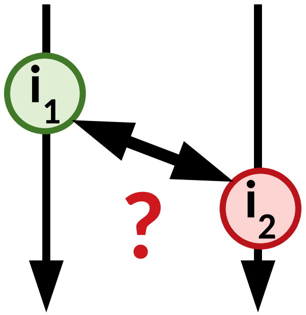

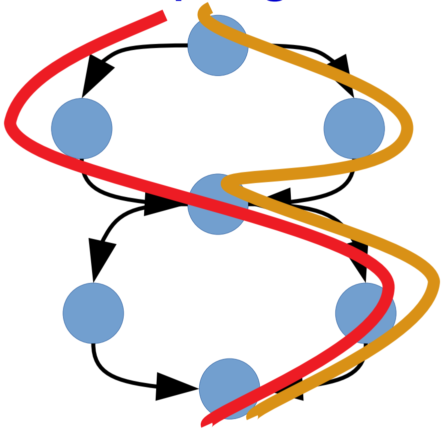

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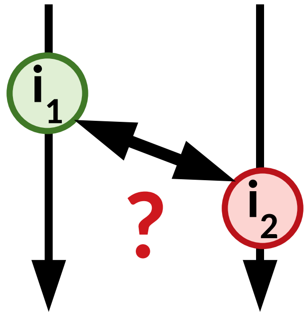

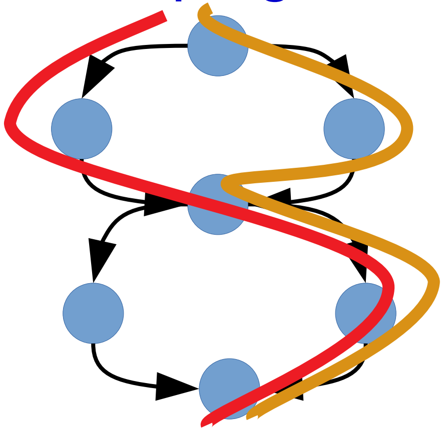

The *position* in the DAG relates the paths

Temporal Alignment

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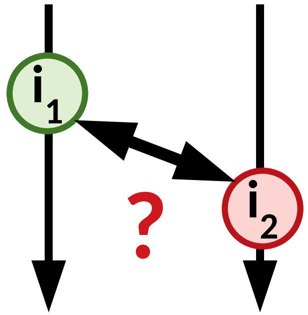

How can we extend the acyclic case?

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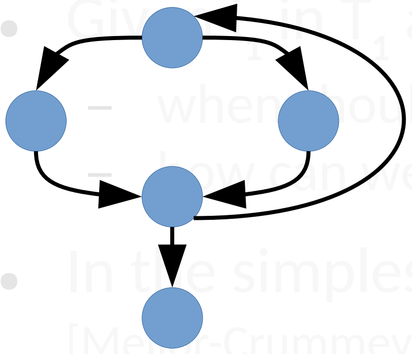
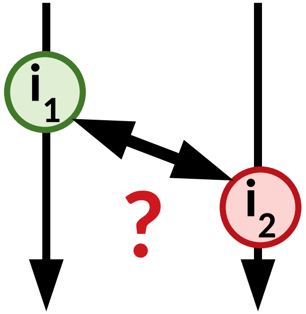


We can unwind the loop to make it logically acyclic

- Now consider the case where cycles can occur... [Sumner, ASE 2013]



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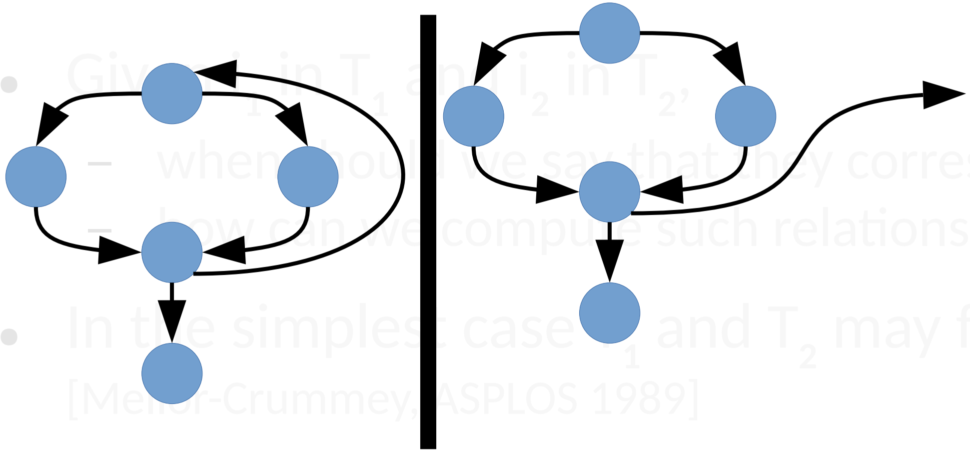

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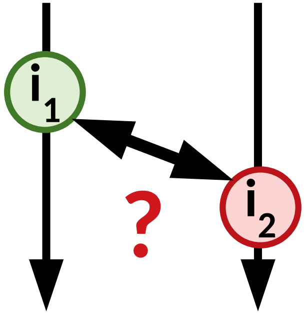

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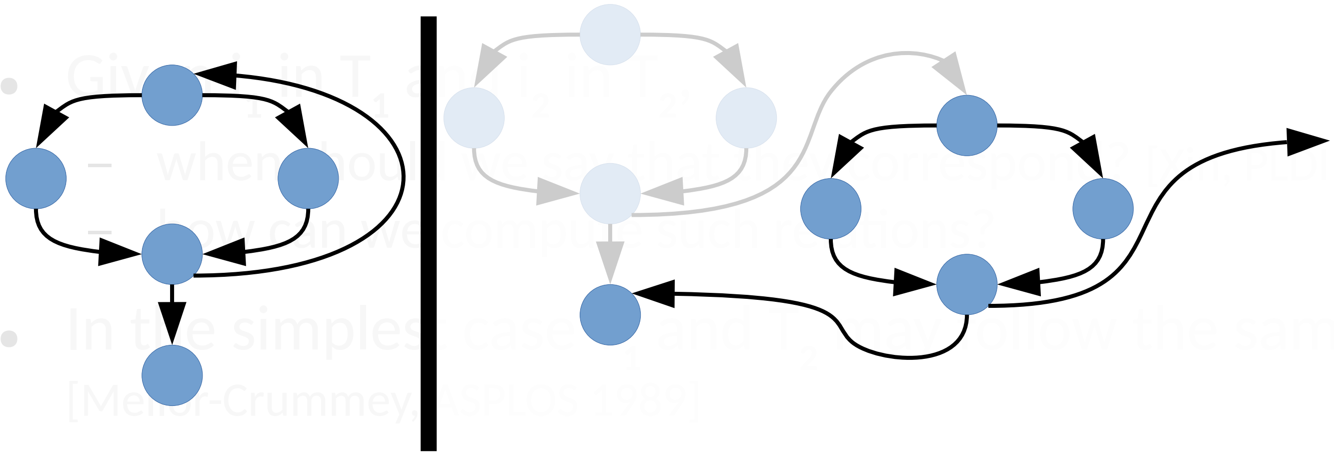

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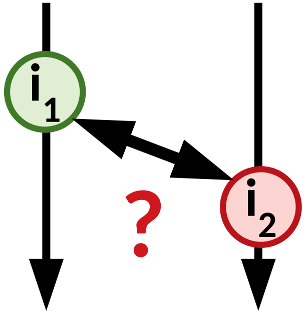

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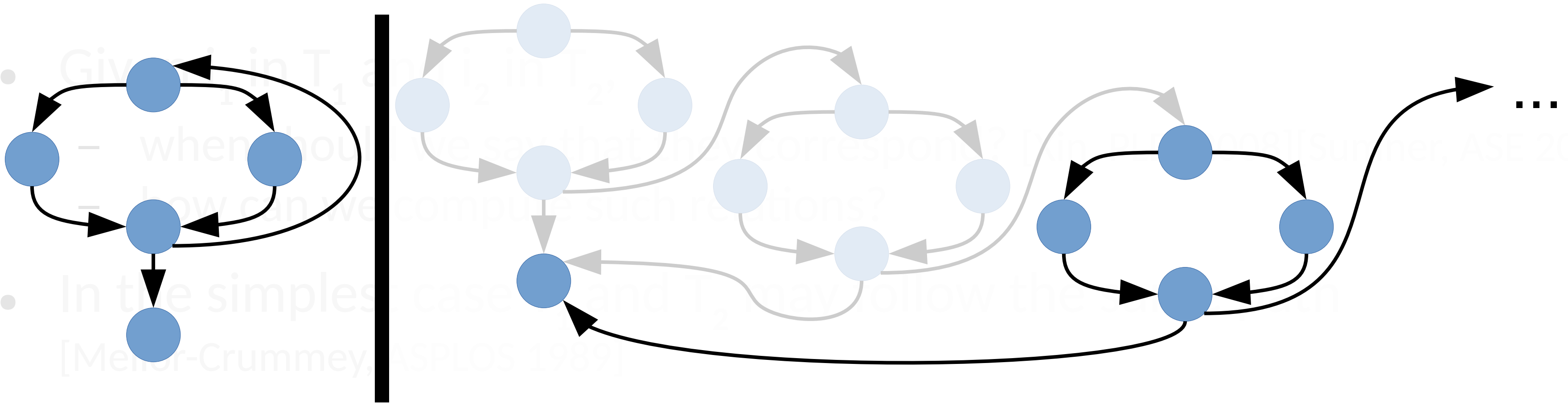

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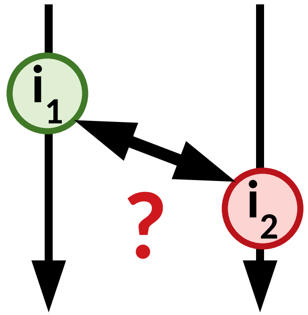

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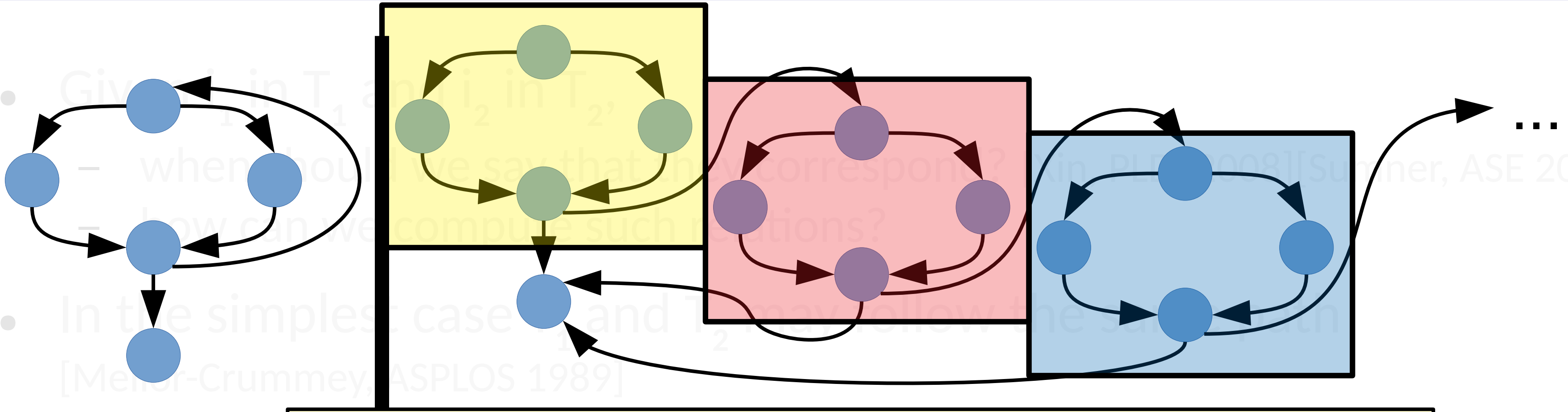
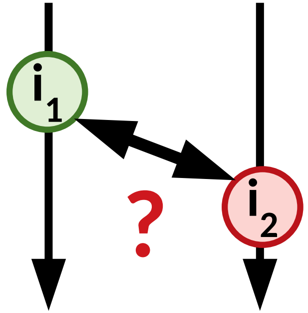


These are different iterations of one loop.
A counter for *each active loop* suffices (mostly).

- Now consider the case where cycles can occur… [Sumner, ASE 2013]



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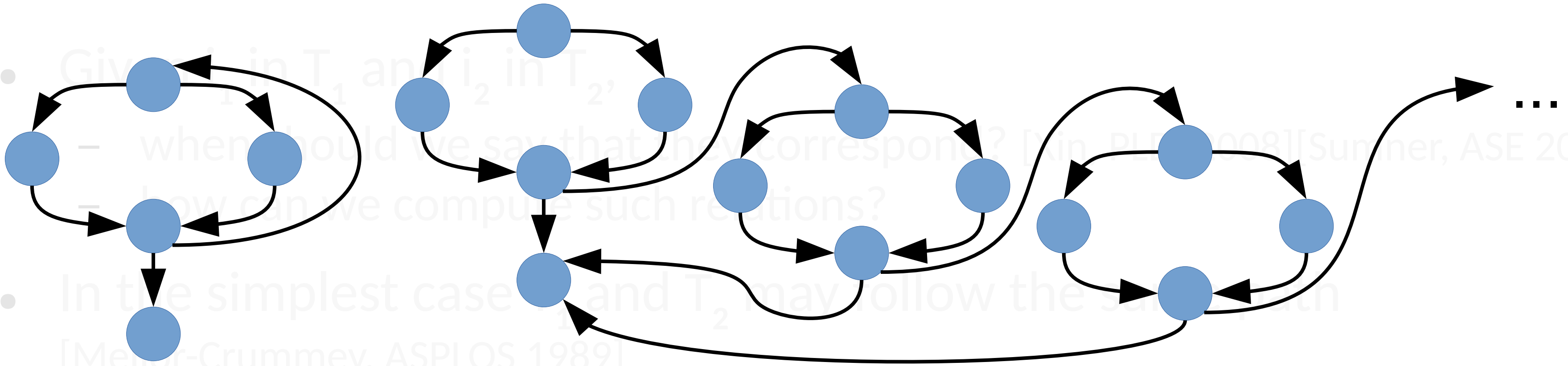

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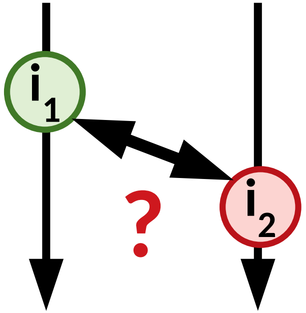

How can we extend the acyclic case?

1 counter per active loop
+ the call stack disambiguates!

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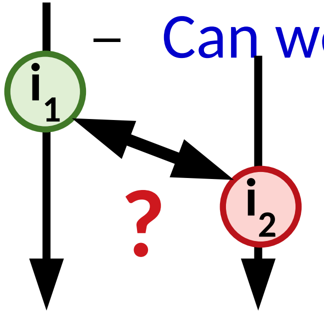
  - Can we ***efficiently*** represent this?



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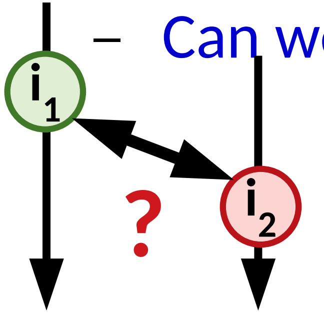

Call stack/context	Iteration stack	Instruction ID

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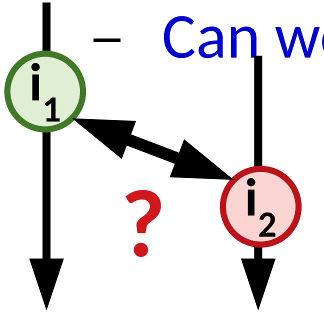

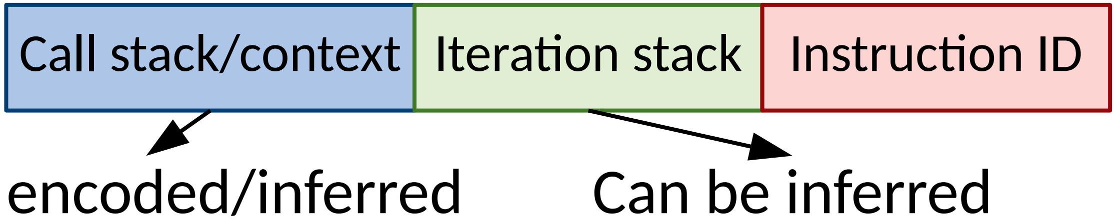

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If you allocated other stuff in only one run,
this can be true even without ASLR!

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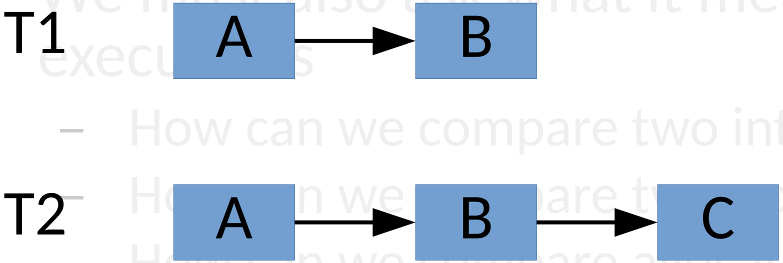

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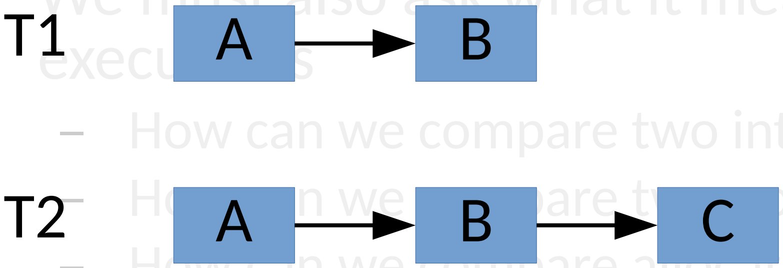

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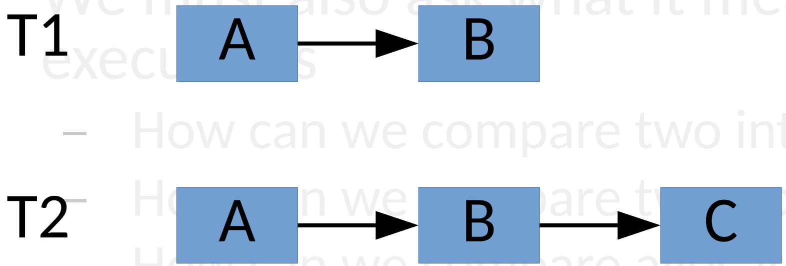

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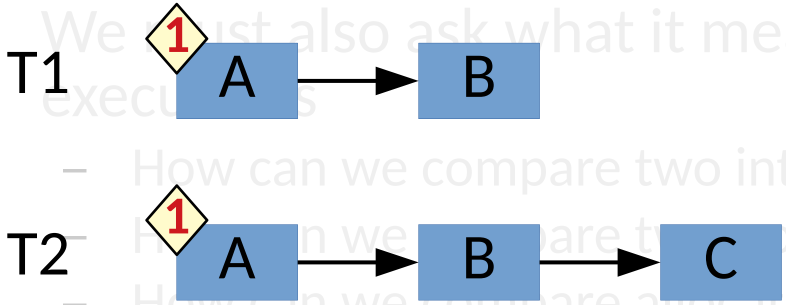

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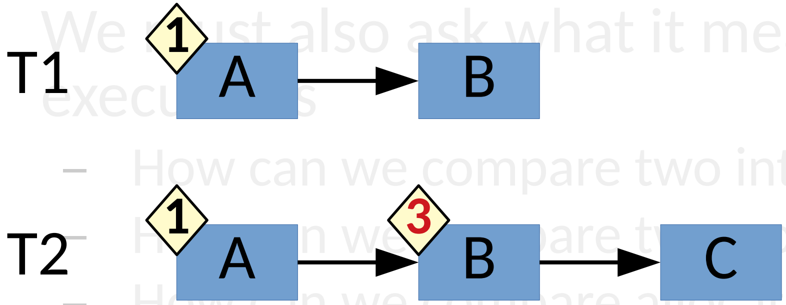

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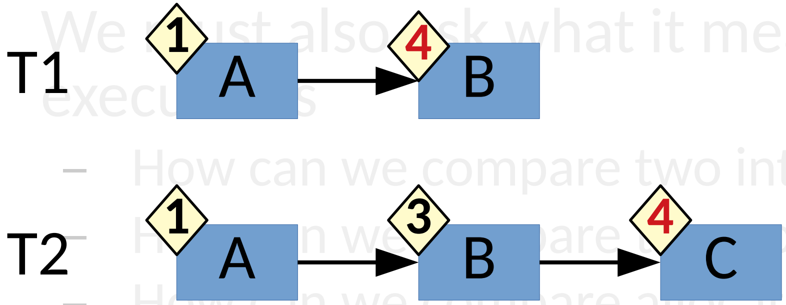

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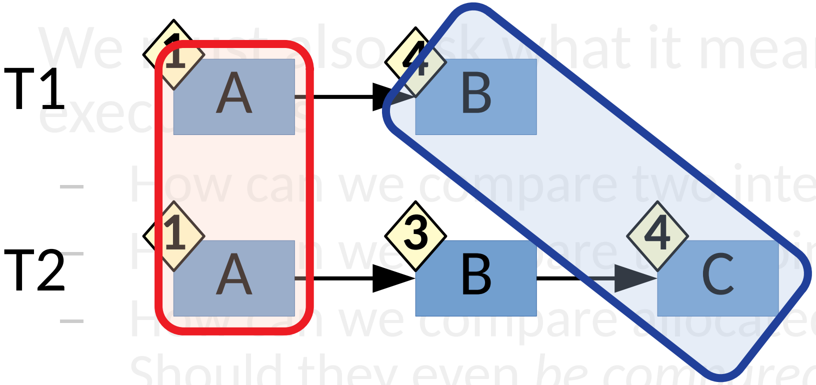

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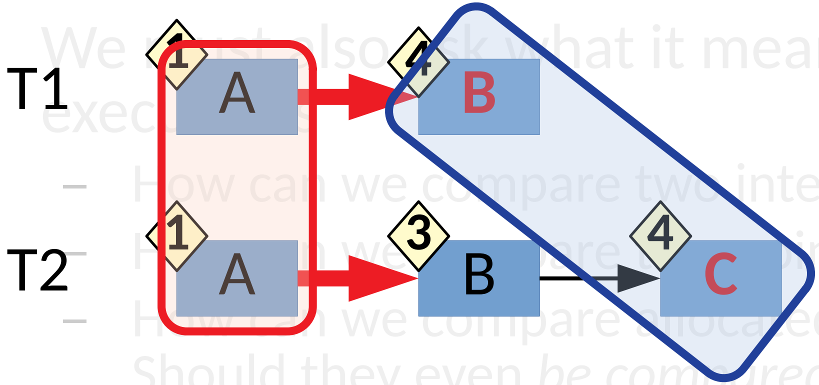

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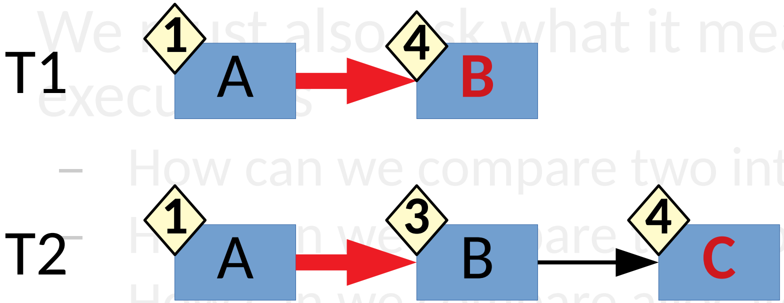

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- Again, the *semantics* of the program dictate the solution
  - Identify heap allocations by the *aligned time* of allocation

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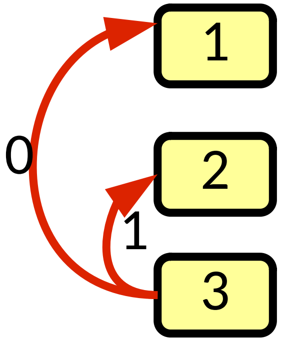


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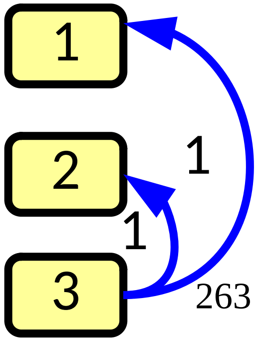

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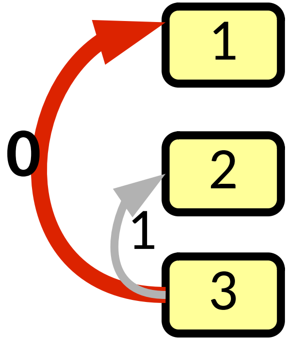


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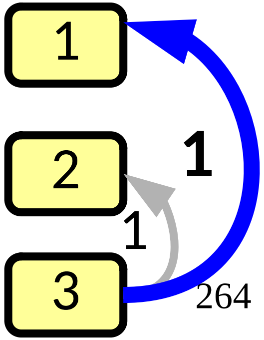

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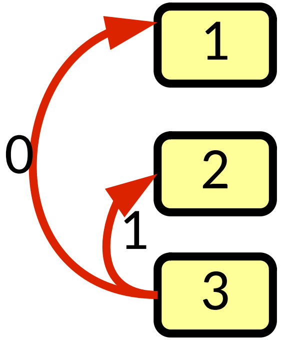


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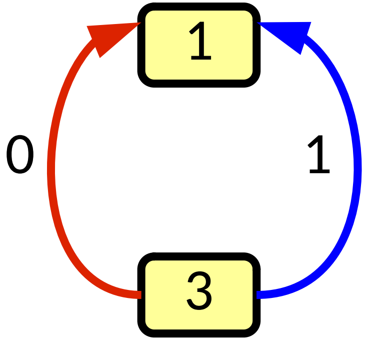


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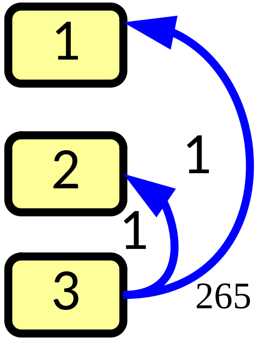

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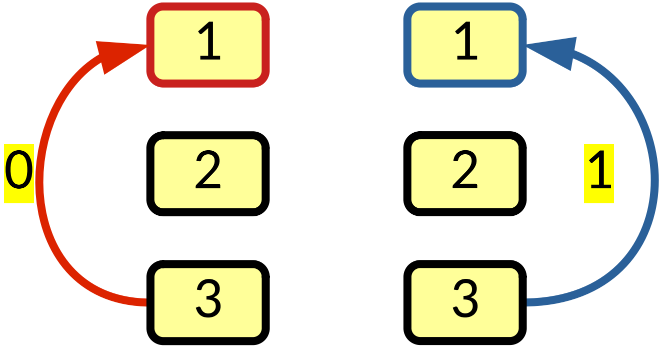

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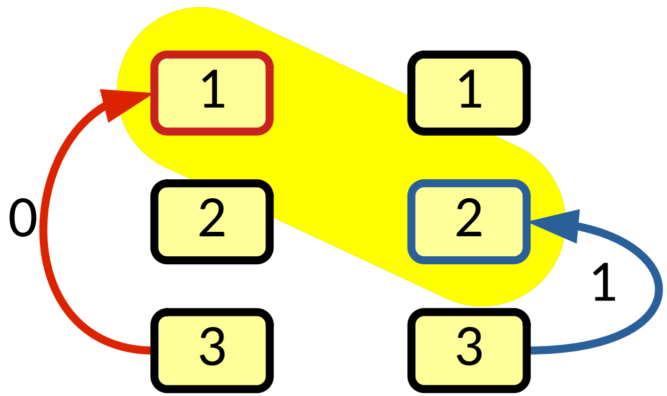

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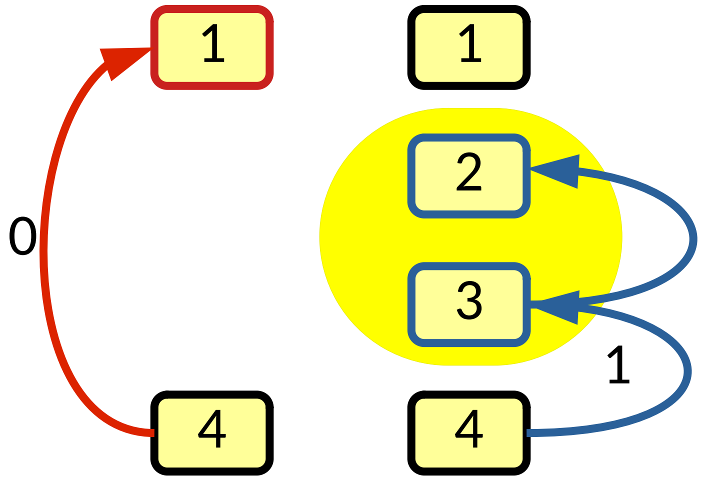

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- Recall: Dynamic slicing could not handle execution omission,
  but dual slicing can!
- Dual slices can be effective for concurrent debugging & exploit analysis
  [Weeratunge, ISSTA 2010][Johnson, S&P 2011]

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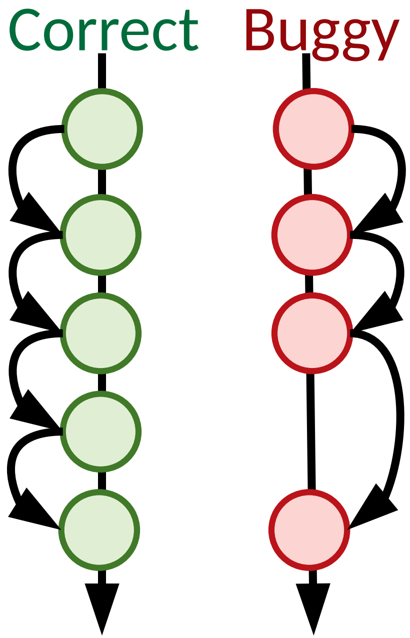
  - Can answer "Why" and "Why not" questions about behavior & differences [Ko, ICSE 2008]



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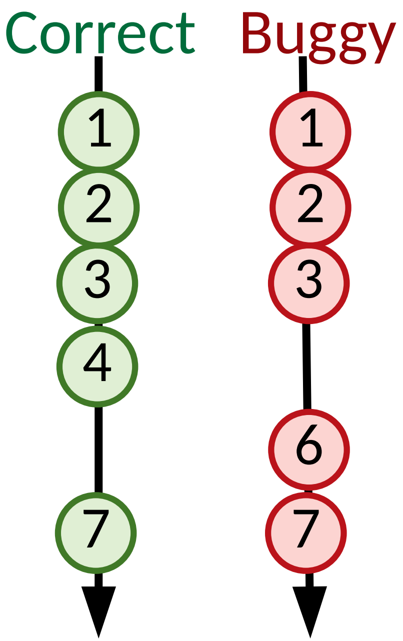

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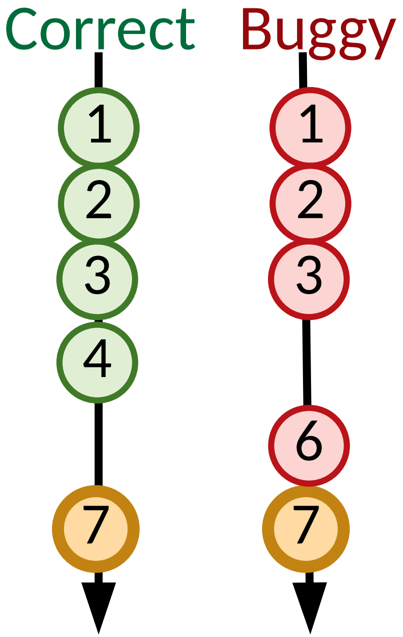

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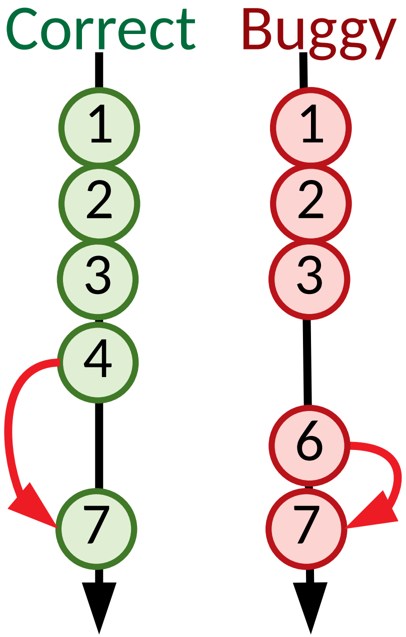

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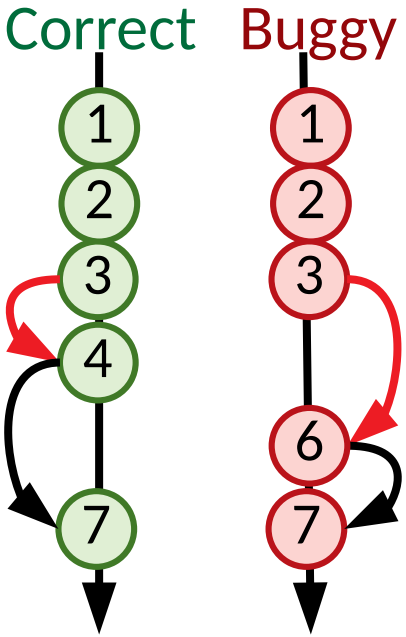

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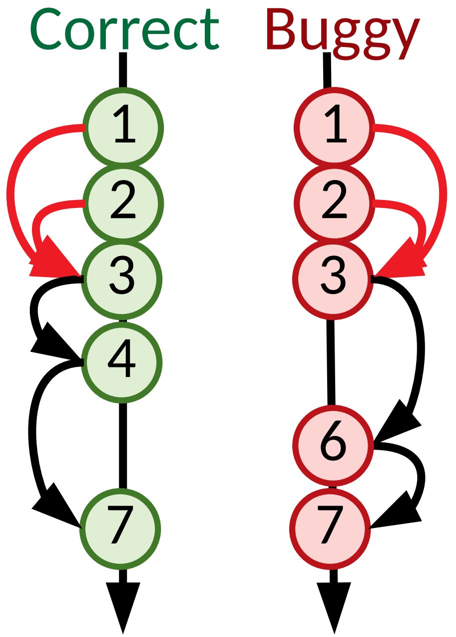

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Dual slicing captures *differences*, not ***causes***.
What does that mean here?

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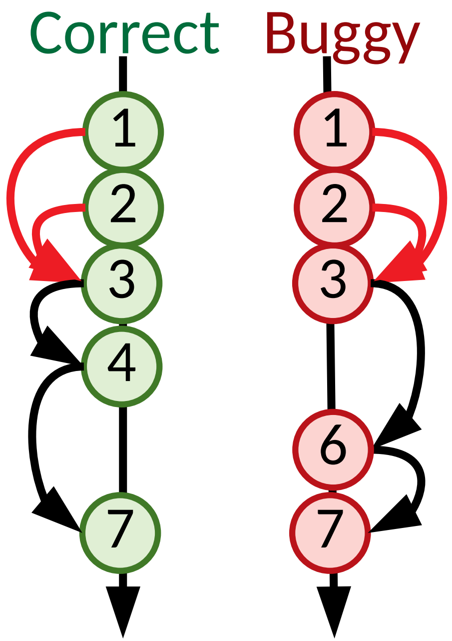

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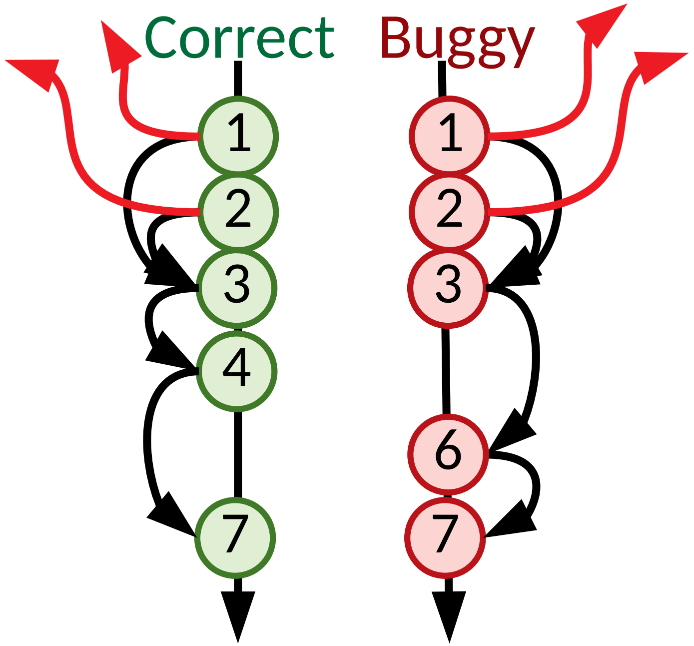

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The cost of these extra edges is high in practice!
All transitive dependencies…

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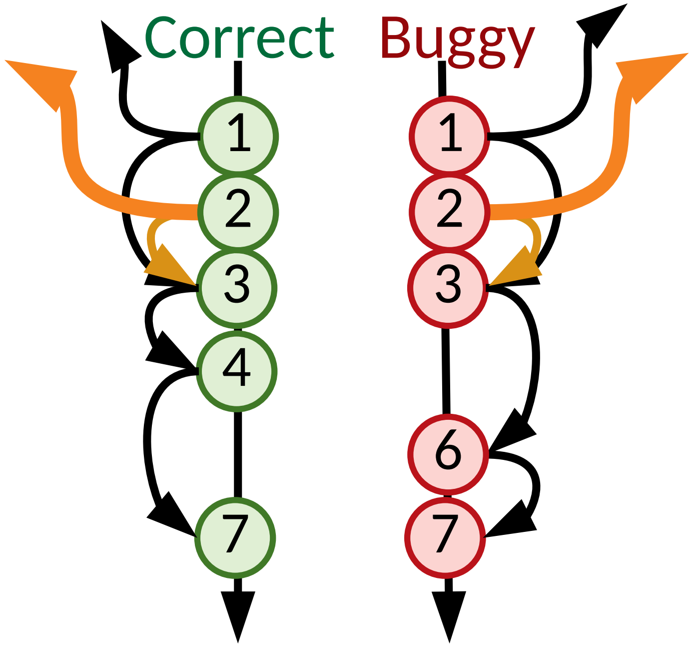

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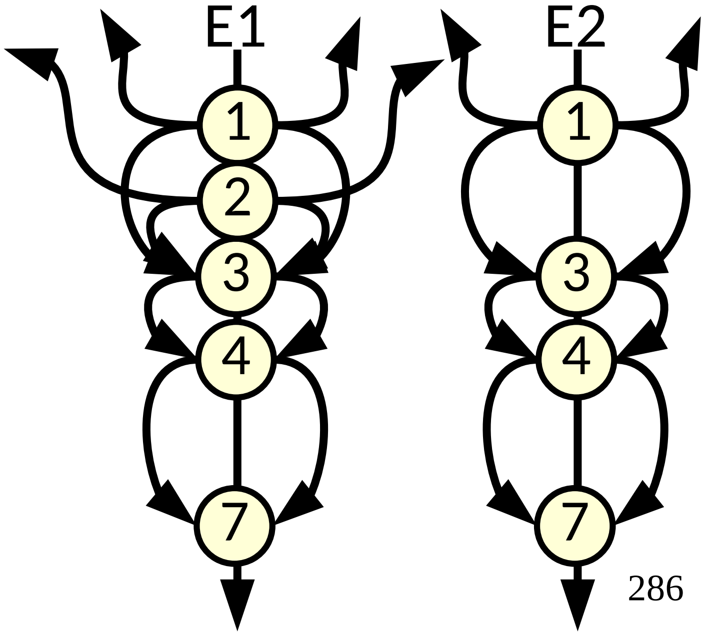

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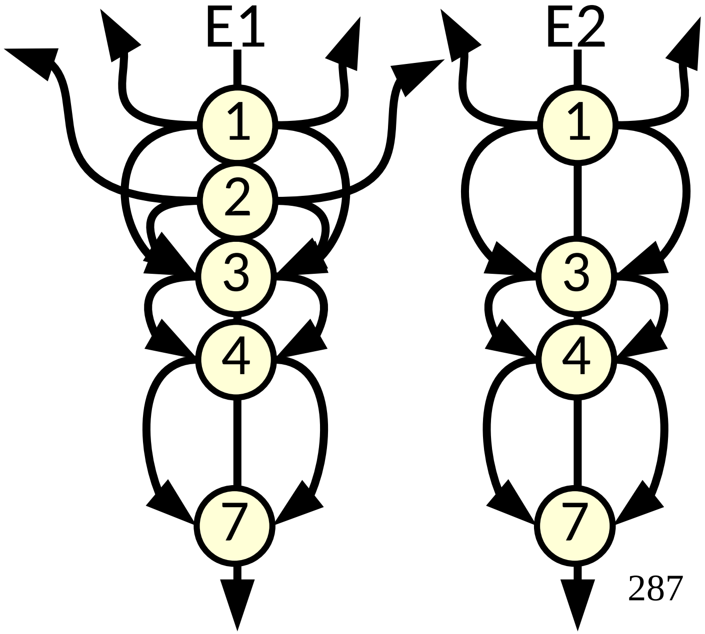

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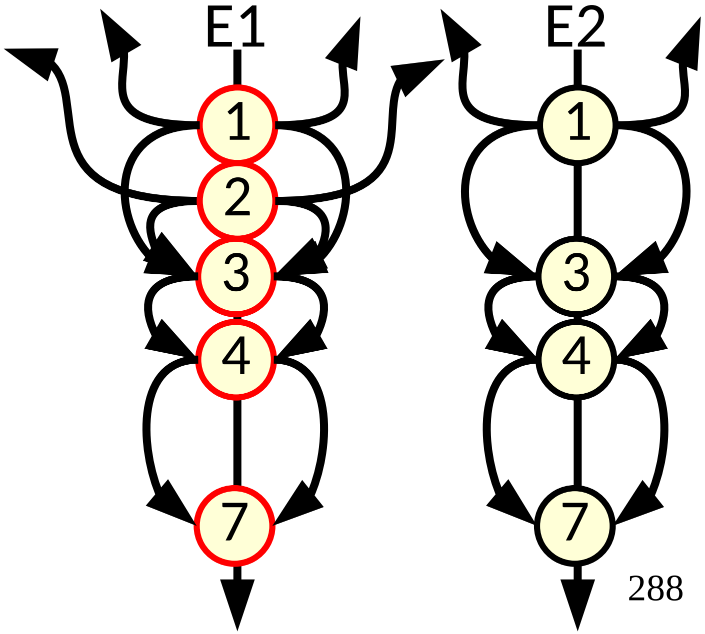

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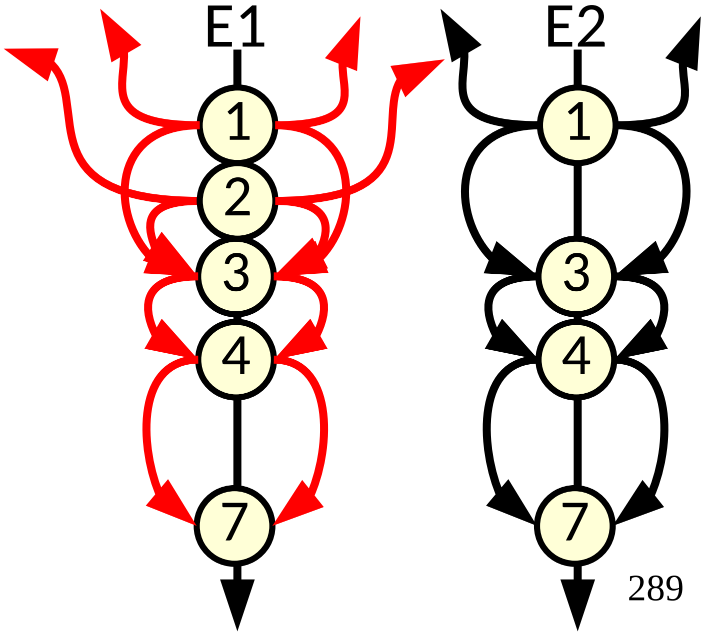

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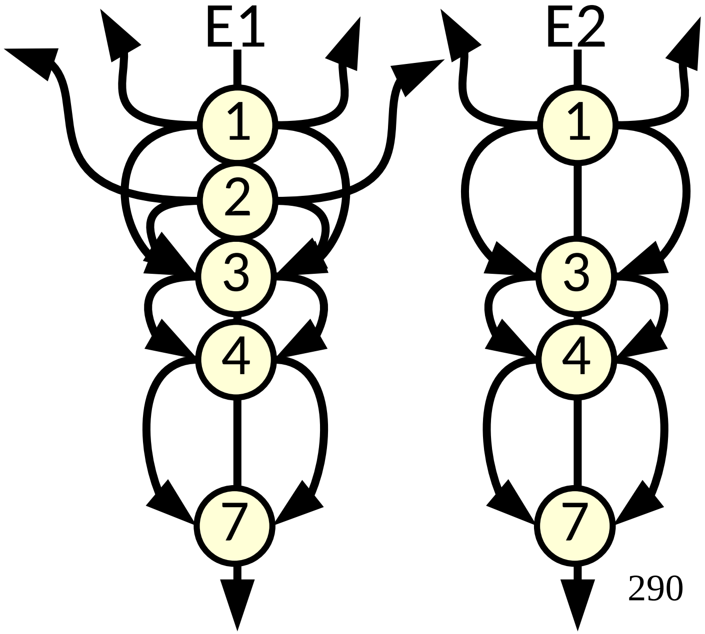
What big challenges do you see with these 2 approaches?



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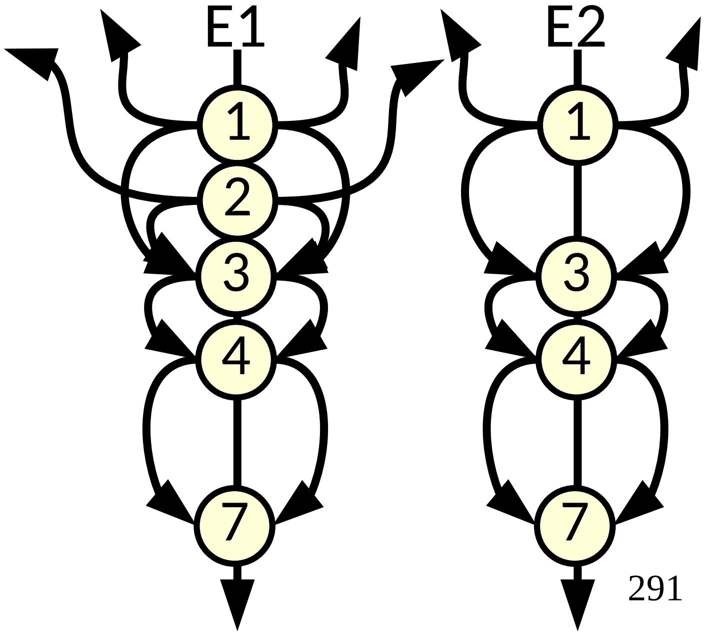

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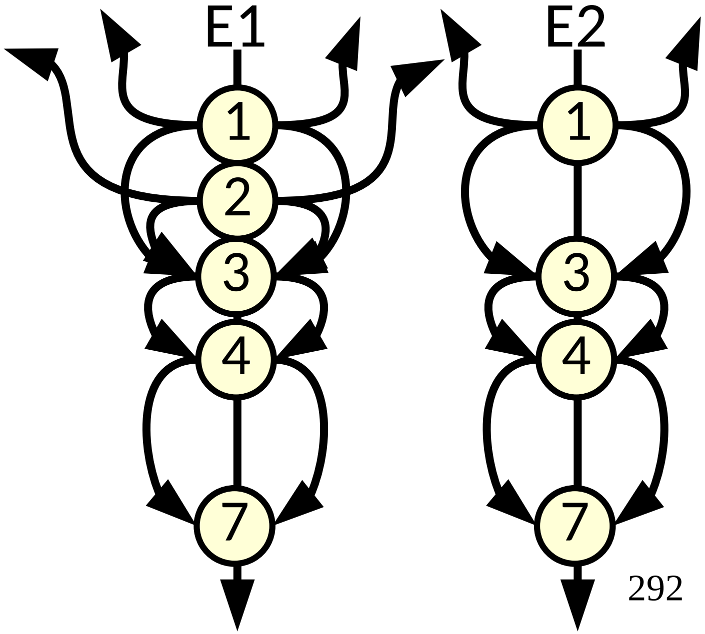

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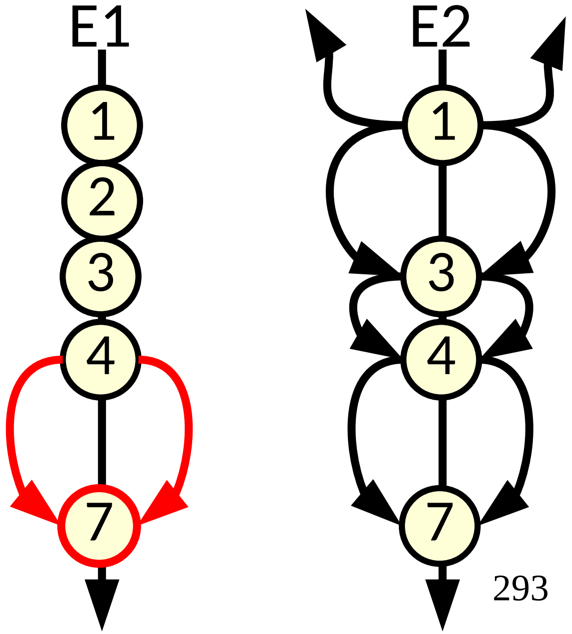

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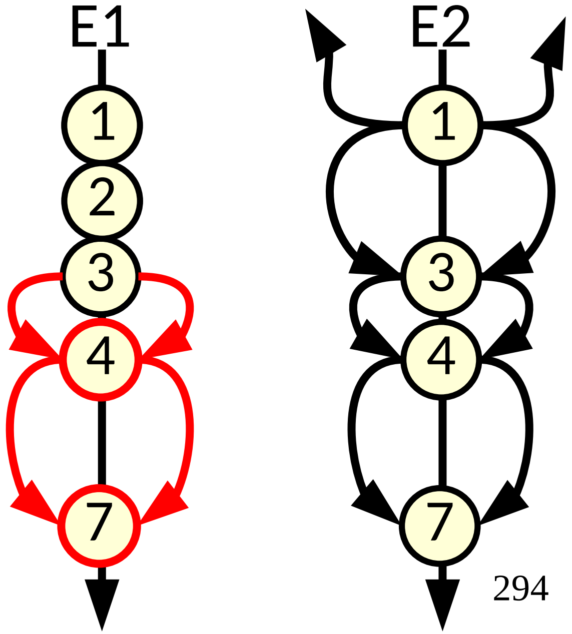

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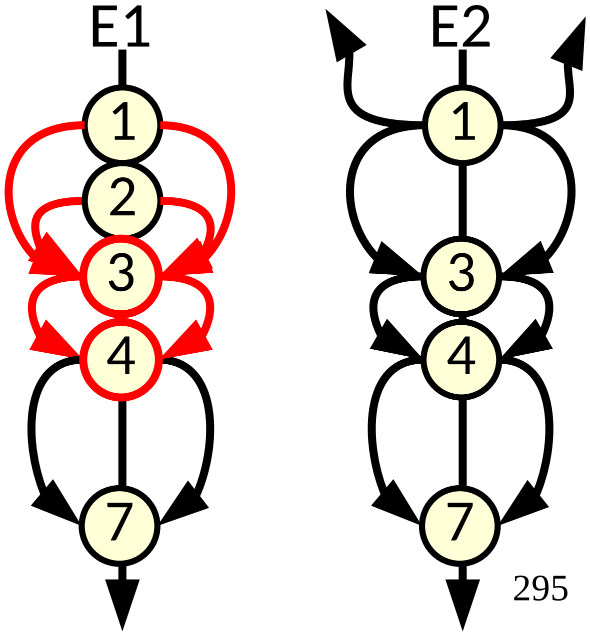

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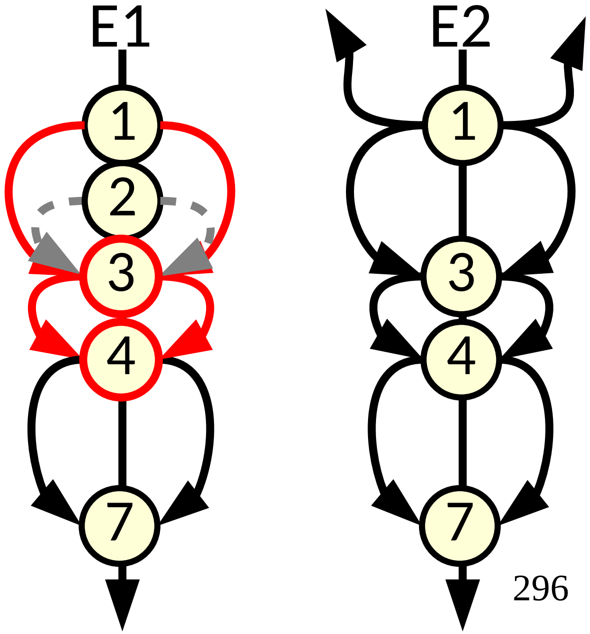

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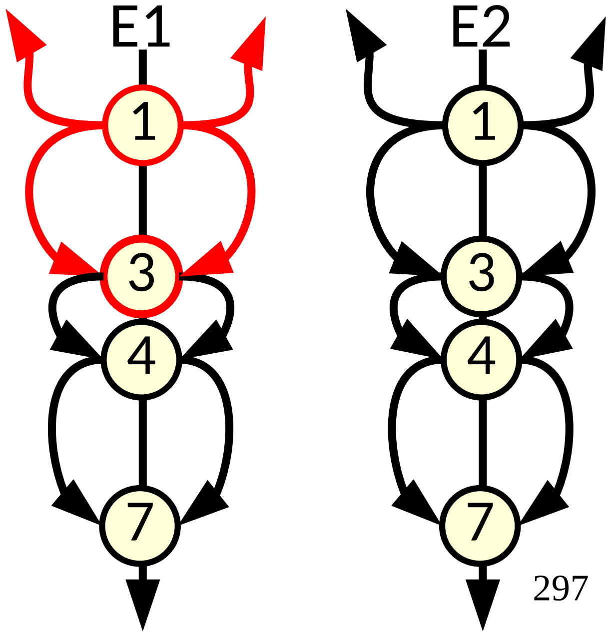

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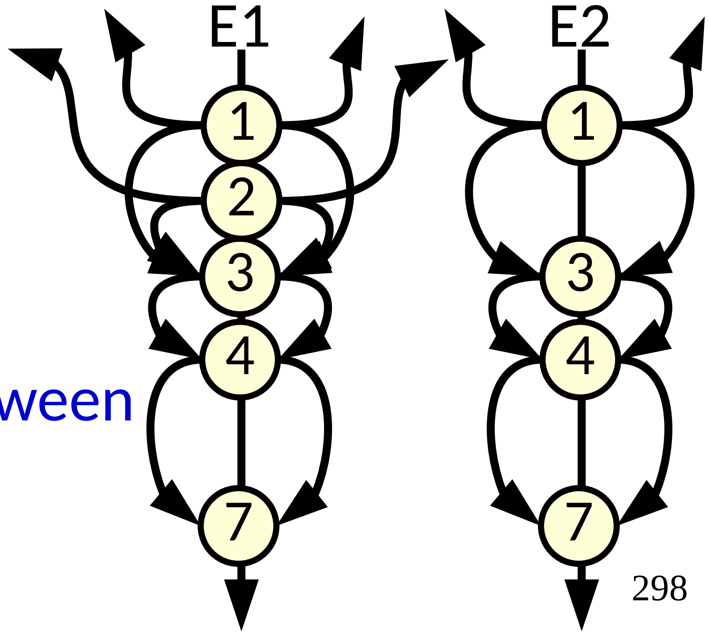
- There are currently unknown trade offs between tractability, intuitiveness, and correctness



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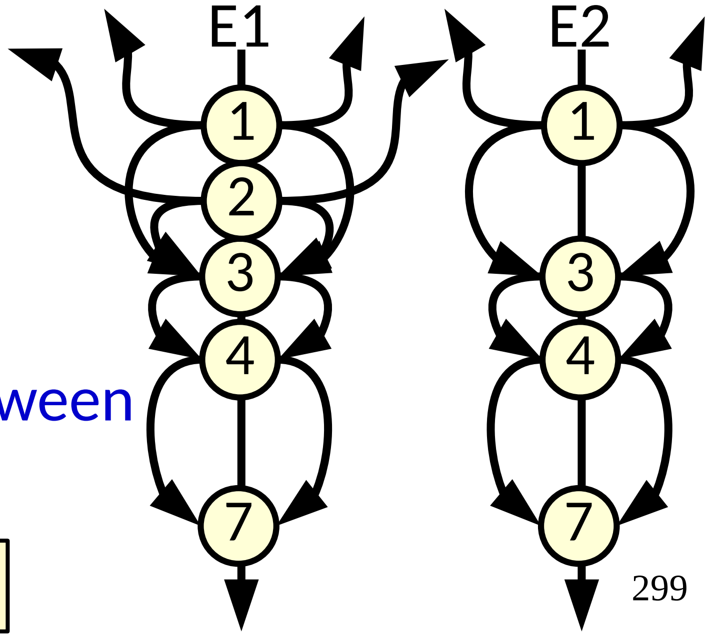
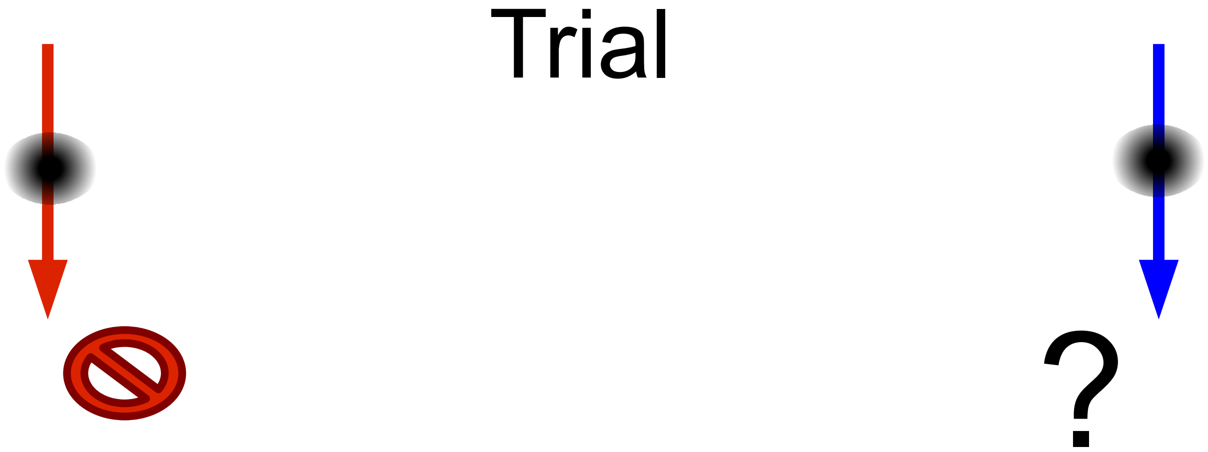


Even local blame is actually challenging

Adding Causation

- Causation is often framed via “alternate worlds” & “what if” questions…
  - We can answer these causality questions by running experiments!

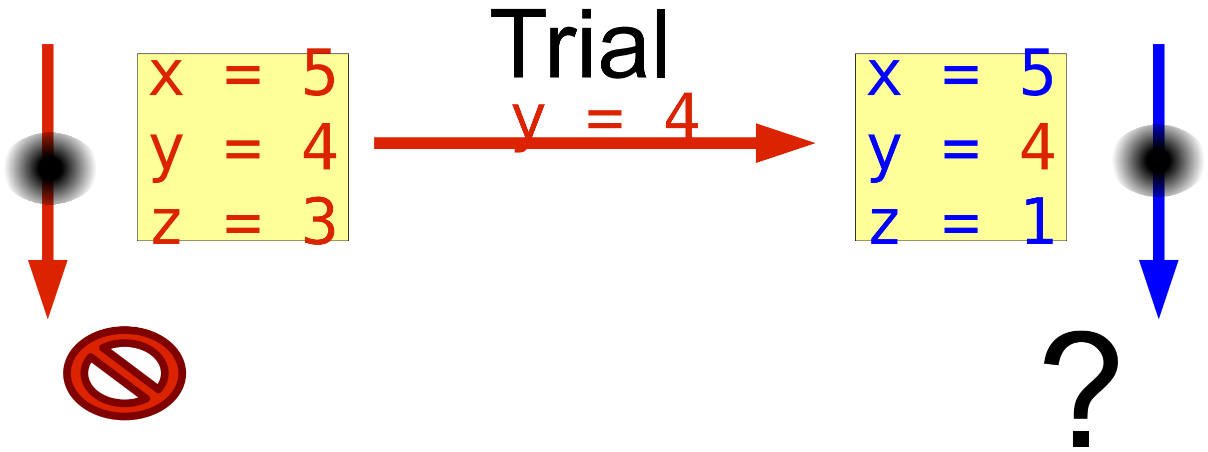
What Should We Blame?



What Should We Blame?

Trial

What Should We Blame?



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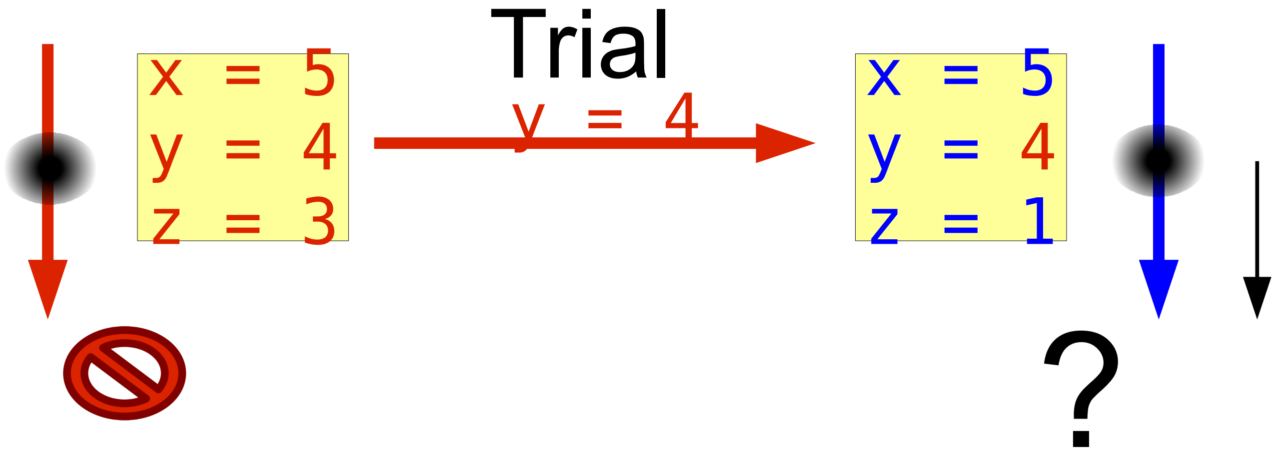

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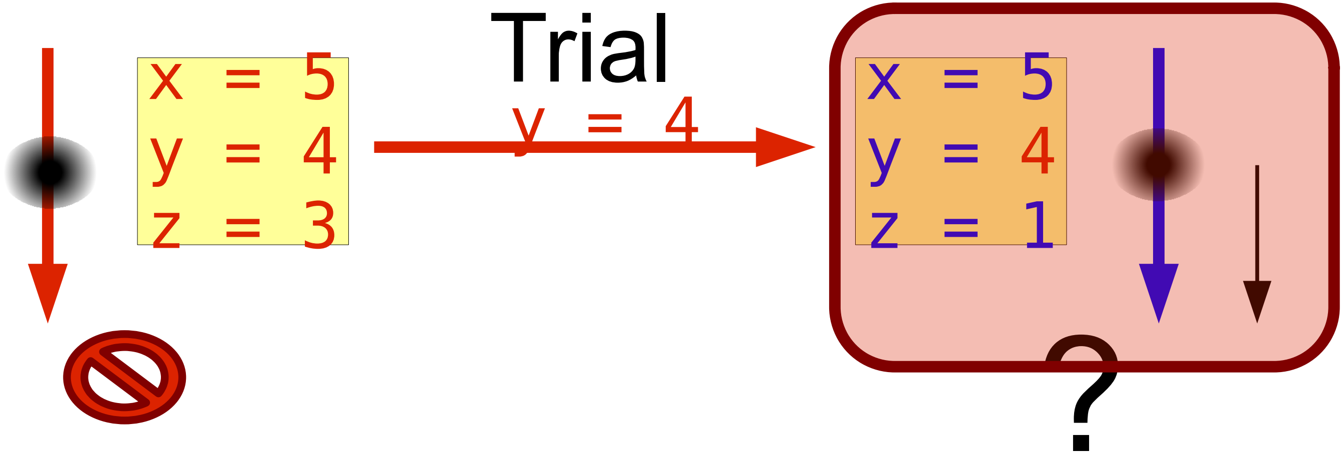

What does this patched run even mean?

Example – Altered Meaning

```
x ← input()
y ← input()
z ← input()
if y+z > 10:
  y ← 5
else: y ← y+1
print(y)
```

Buggy

```
x ← 0
y ← 7
z ← 3
if False:

else: y ← 8
print(8)
```

Correct

```
x ← 1
y ← 3
z ← 6
if False:

else: y ← 4
print(4)
```

Example – Altered Meaning

```
1)x ← input()
2)y ← input()
3)z ← input()
4)if y+z > 10:
5)   y ← 5
6)else: y ← y+1
7)print(y)
```

Buggy

```
x ← 0
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x ← 1
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What should we blame here?

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Buggy	Trial	Correct
x ← 0	x ← 0	x ← 1
y ← 7	y ← 7	y ← 3
z ← 3	z ← 3	z ← 6
if False:		if False:
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Buggy	Trial	Correct
x ← 0		x ← 1
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Buggy	Trial	Correct
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- New control flow unlike original runs
- Occurs in large portion of real bugs

Dual Slicing

```
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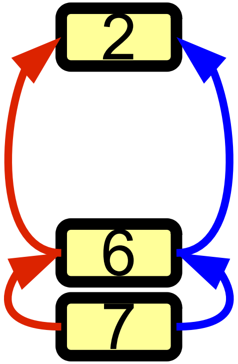

Correct

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Extract

```
2)y ← input()
6)y ← y+1
7)print(y)
```

Example – Extracted Meaning

```
2)y ← input()
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Buggy	Trial	Correct
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Buggy	Trial	Correct
y ← 7	y ← 7	y ← 7
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Example – Extracted Meaning

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2)y ← input()
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Buggy	Trial	Correct
y ← 7	y ← 7	y ← 7
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Trial can now correctly blame y

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- Causation is often framed via “alternate worlds” & “what if” questions…
  - We can answer these causality questions by running experiments!
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  - How did the correct run behave differently than the buggy one?
  - These questions do not have the same answer!
- In practice, there are additional issues,
  and even defining causation in this context needs further research.
  - Did we want to blame only y in the example?
  - Pruning blame on y is necessary in many real cases, can they be refined?
  - Can it be done without execution? With a stronger statistical basis?

Summing Up

Key Challenges

- Identifying the information you care about
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- Doing some of the work ahead of time
  - What can you precompute to improve all of the above?

Summary

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- Analyze the information online or offline
- The precise configuration must be tailored to the objectives & insights
  - Compiled vs DBI
  - Online vs Postmortem
  - Compressed, Encoded, Samples, …
  - …