Program Validation by Symbolic and Reverse Execution

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Computer Programs

Introduction
- Computer Programs
- Program Errors (aka ‘Bugs’)
- Topic of My Thesis
- Program Life-cycle
- My Thesis (What)
- My Thesis (How)
- Plan

Reverse Execution

Program Validation by Symbolic Execution

Concluding Remarks

Programs are everywhere.

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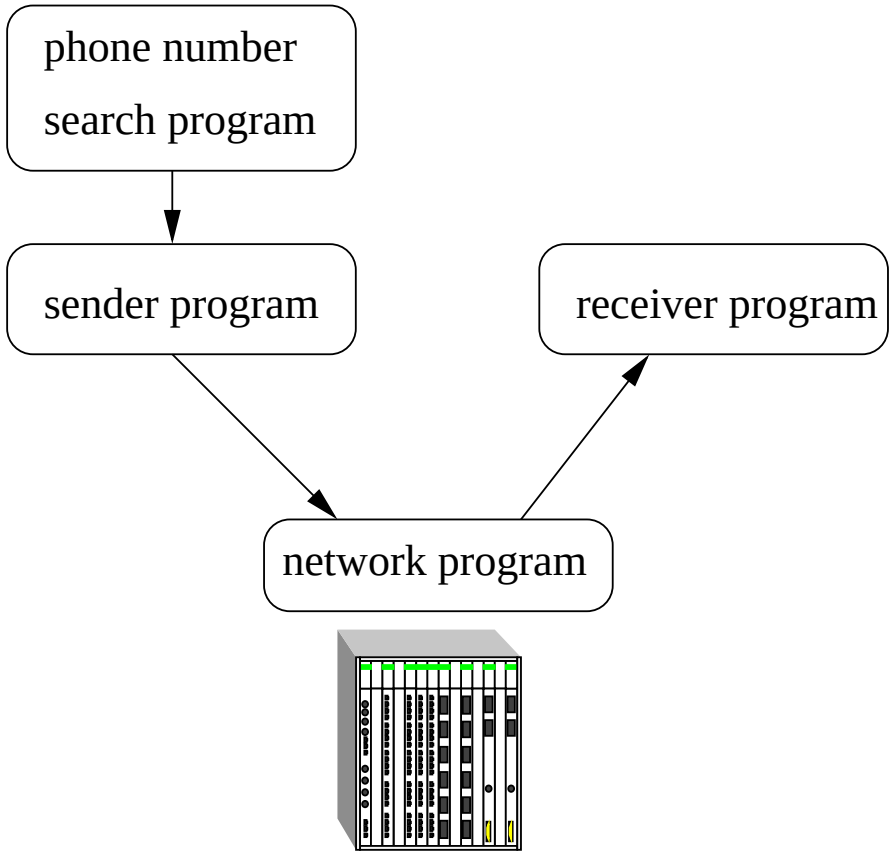

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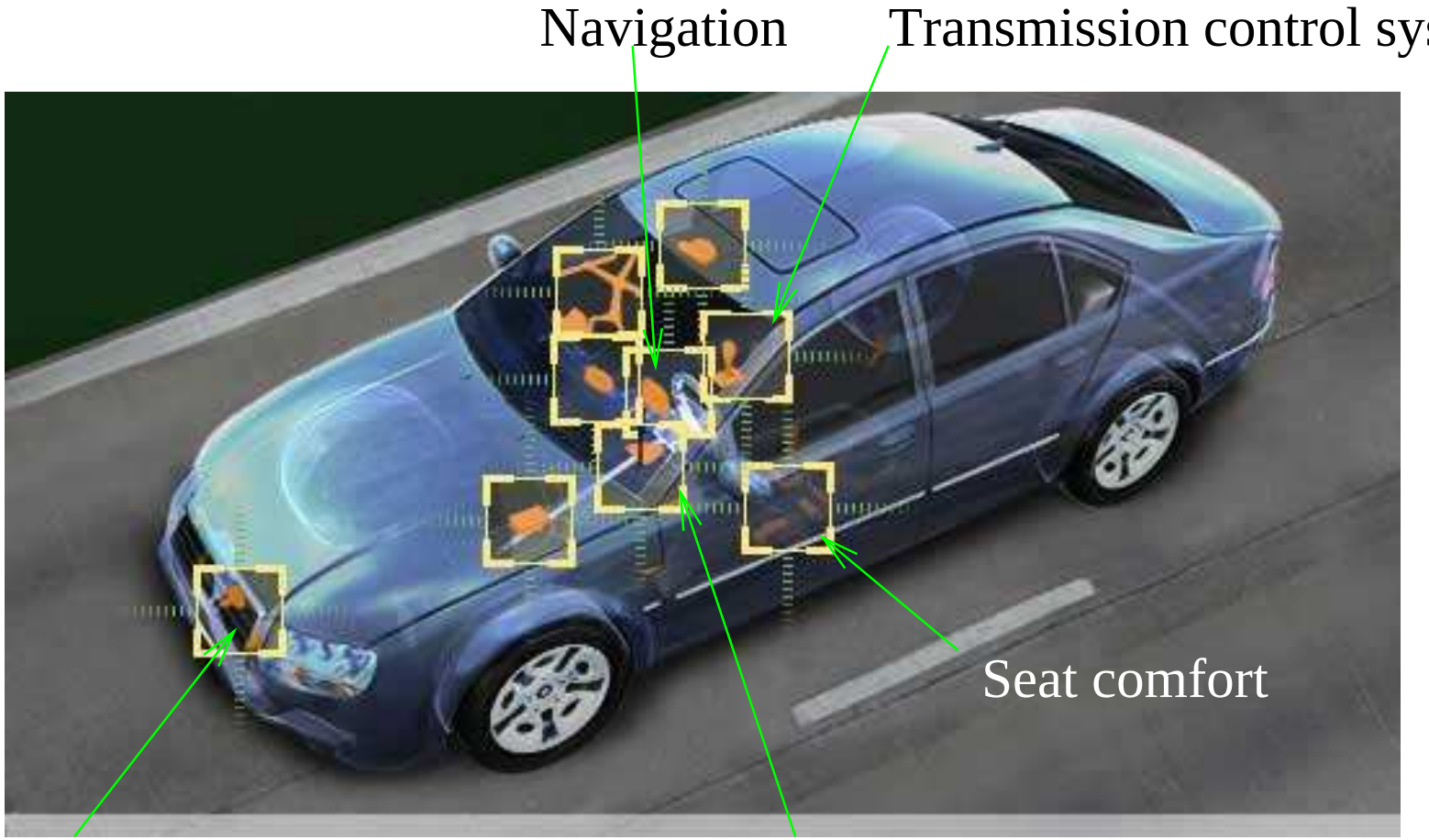

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- Ariane 5: an unmanned rocket
- Everything is controlled by programs.

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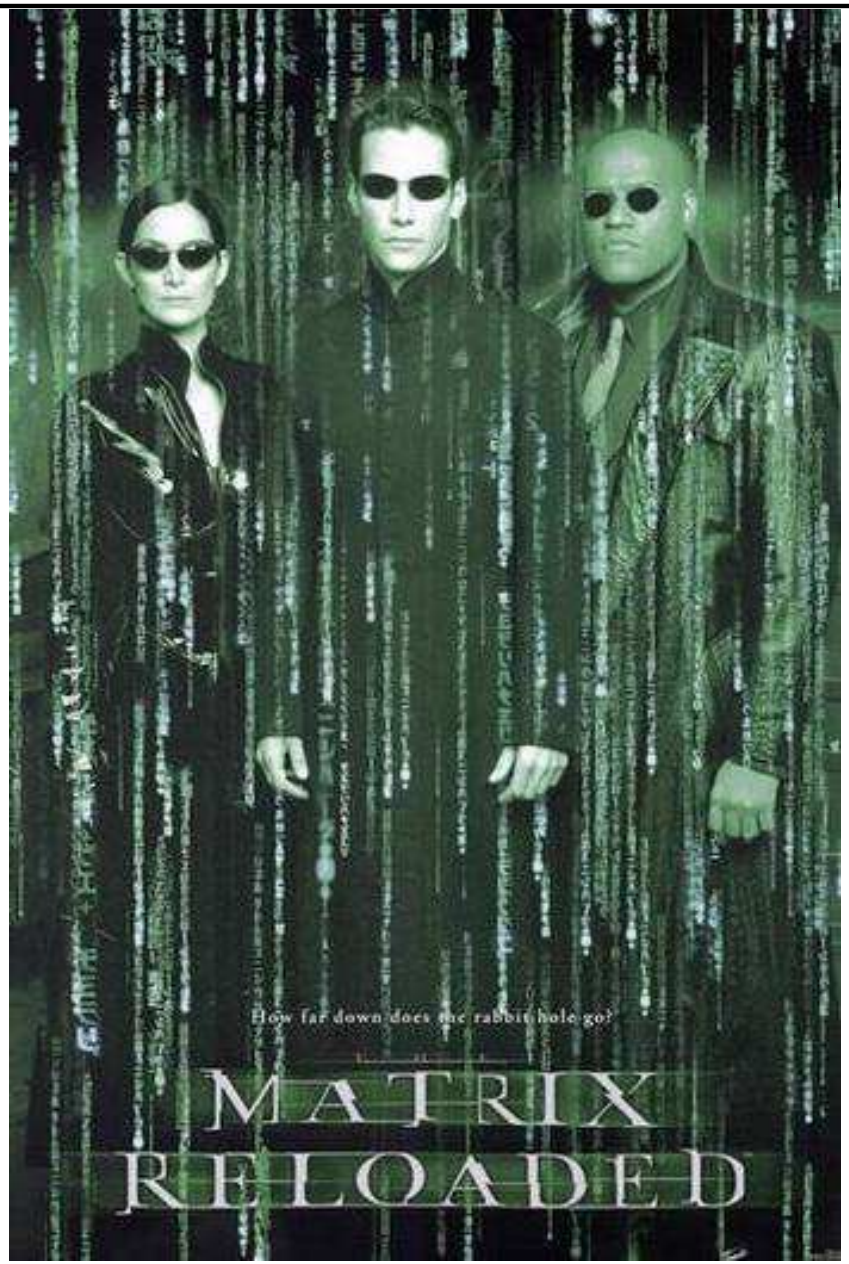

Who knows?
We may be living our lives as programs in the Matrix.

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Bugs are everywhere.

A problem has been detected and windows has been shut down to prevent damage
to your computer.

The problem seems to be caused by the following file: SPCMDCON.SYS

PAGE_FAULT_IN_NONPAGED_AREA

If this is the first time you've seen this Stop error screen,
restart your computer. If this screen appears again, follow
these steps:

Check to make sure any new hardware or software is properly installed.
If this is a new installation, ask your hardware or software manufacturer
for any windows updates you might need.

If problems continue, disable or remove any newly installed hardware
or software. Disable BIOS memory options such as caching or shadowing.
If you need to use Safe Mode to remove or disable components, restart
your computer, press F8 to select Advanced Startup Options, and then
select Safe Mode.

Technical information:

*** STOP: 0x00000050 (0xFD3094C2,0x00000001,0xFBFE7617,0x00000000)

*** SPCMDCON.SYS - Address FBFE7617 base at FBFE5000, DateStamp 3d6dd67c

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Is it really OK?

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- Recall of Chrysler Pacifica in 2006
- Summary: ON CERTAIN PASSENGER VEHICLES, THE FUEL PUMP MODULE AND THE POWER TRAIN CONTROL MODULE SOFTWARE MAY ALLOW THE ENGINE TO STALL UNDER CERTAIN OPERATING CONDITIONS.
- Consequence: THIS COULD CAUSE A CRASH TO OCCUR WITHOUT PRIOR WARNING.

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- The Ariane 5 rocket exploded 40 seconds after its launch due to a program bug in 1996.

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CHECKING FOR BUGS

&

LOCATING BUGS

in programs

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PROGRAM VALIDATION

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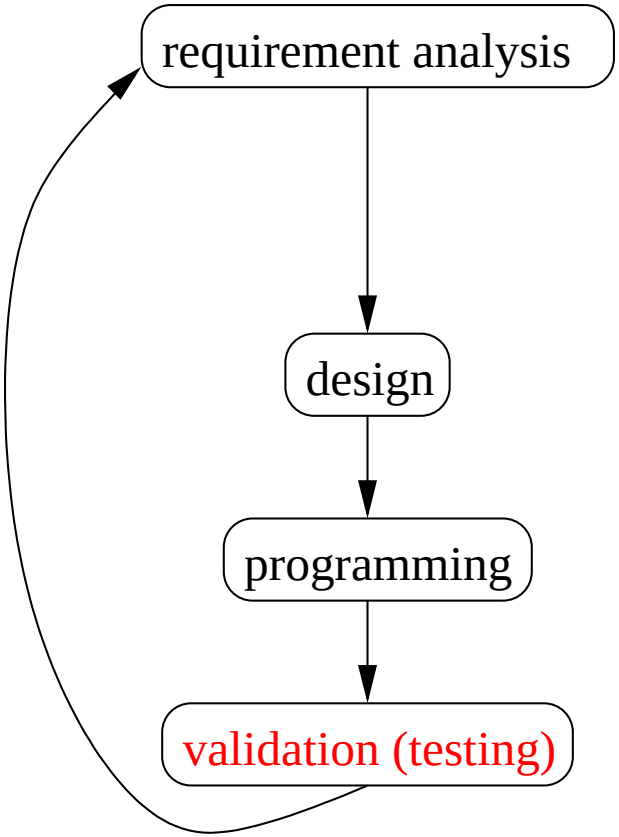

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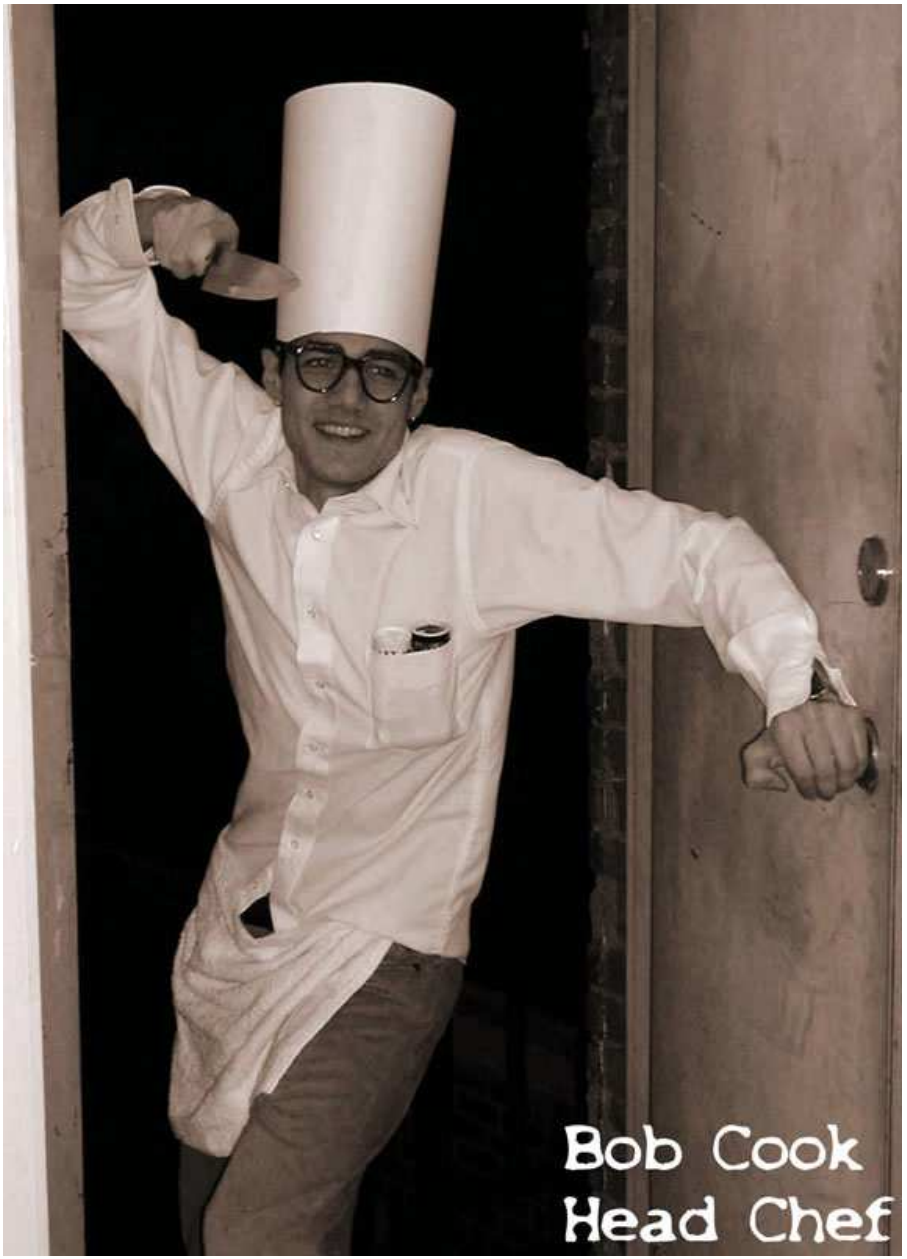

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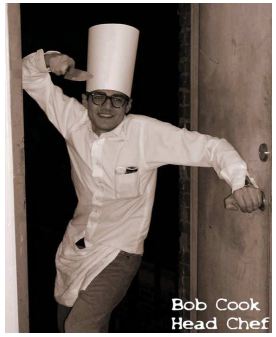

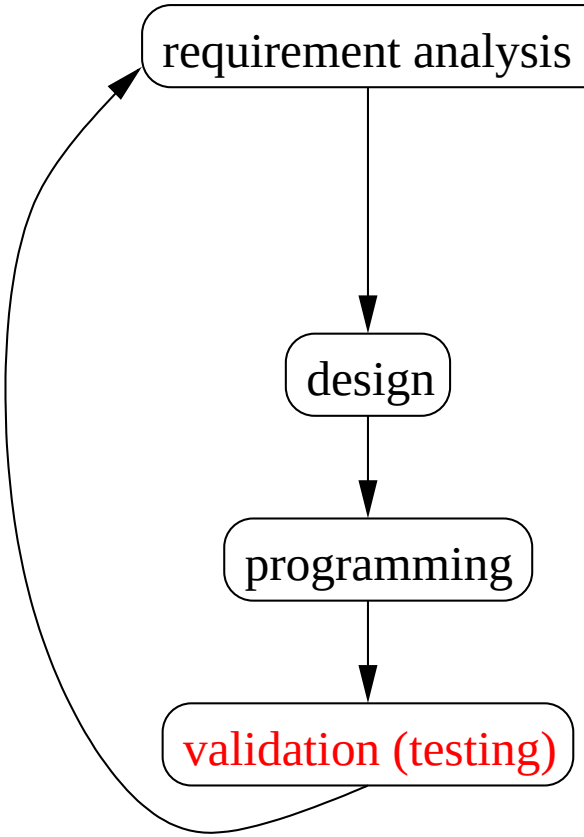

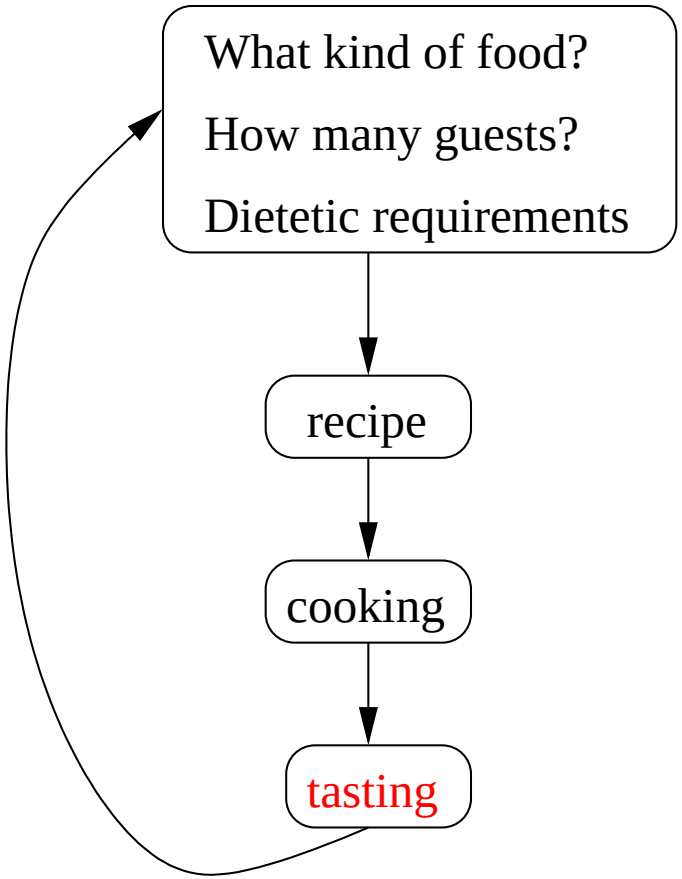

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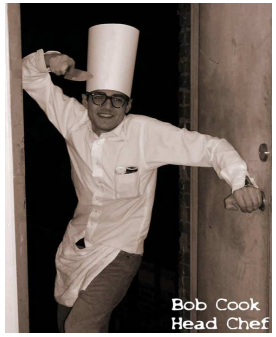

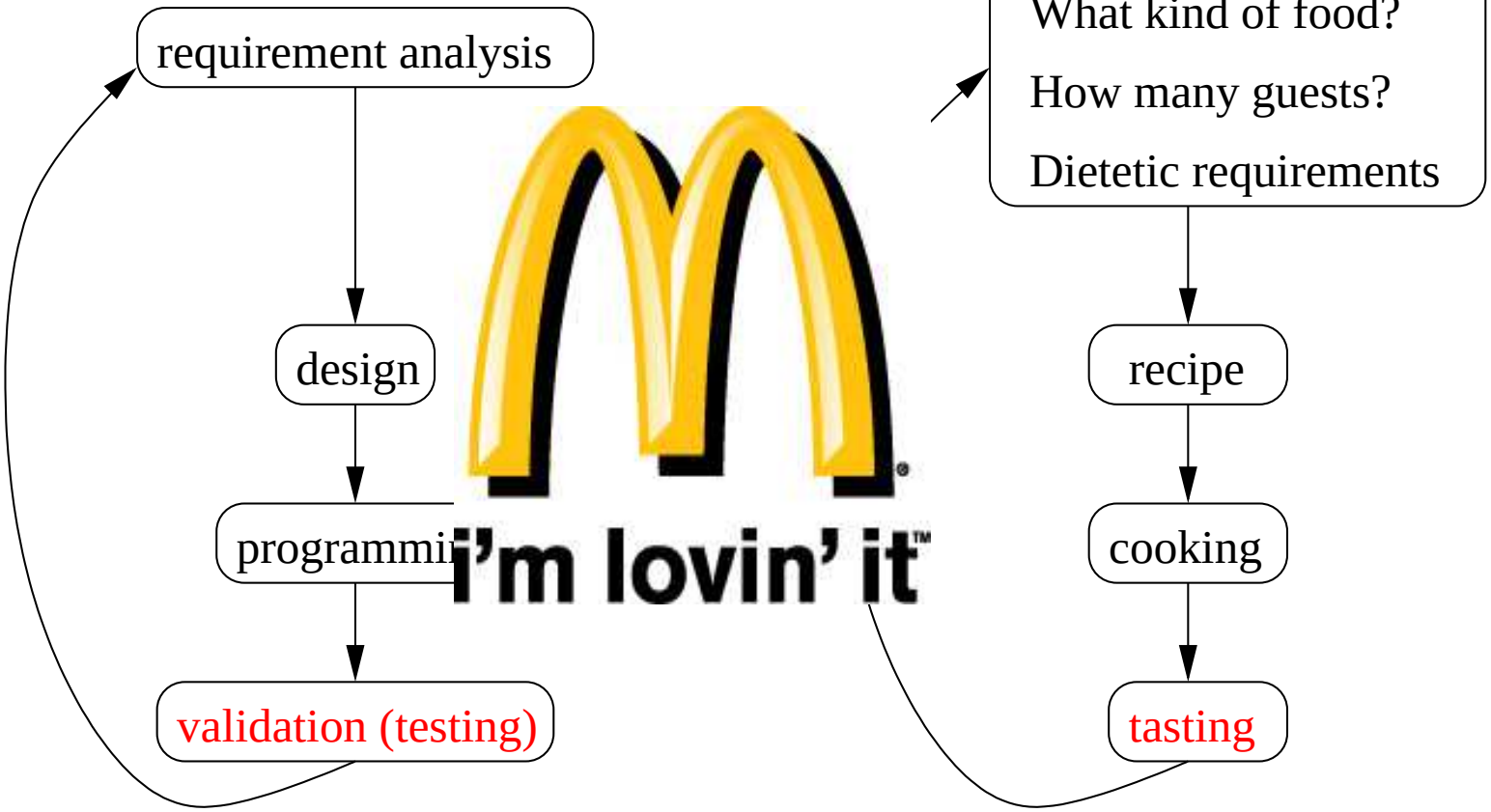

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Program Validation

by Symbolic and Reverse Execution

- Symbolic Execution
  - Checking for Bugs

- Reverse Execution
  - Locating Bugs

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Concluding Remarks

1. Introduction
2. Reverse Execution
   (a) What is it?
   (b) Existing Work?
   (c) Problem?
   (d) Contribution: Dynamic Reverse Code Generation
   (e) Soundness
   (f) Case Study
3. Symbolic Execution
   (a) What is it?
   (b) Existing Work?
   (c) Contribution: Bounded Lazier Initialization
   (d) Soundness and Completeness
4. Concluding Remarks

What?

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Reverse Execution

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- Multiple Variables
- Combination
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- Bounded Buffer Example

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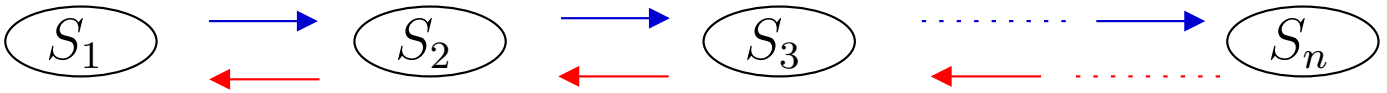
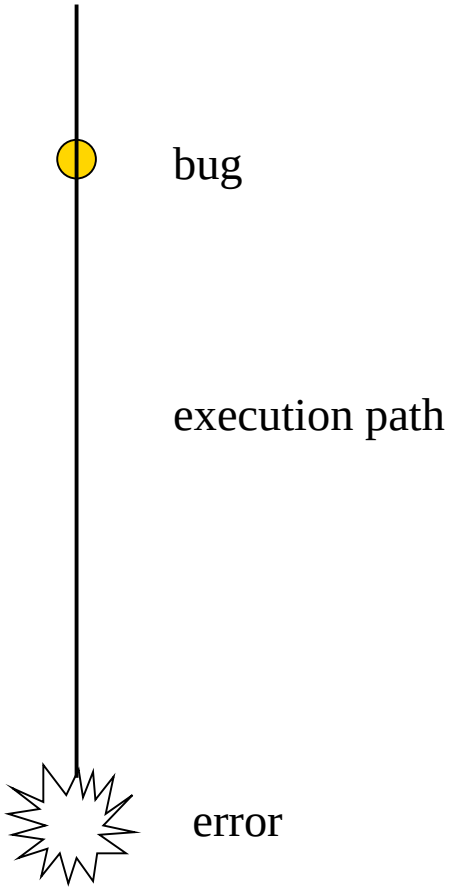
Program Validation by Symbolic Execution

- What is reverse execution?
  - A series of state restorations
- What is execution?
  - A series of state changes



Locating a Bug

- Butterfly Effect: Something as small as the flutter of a butterfly's wings can ultimately cause a typhoon halfway around the world.



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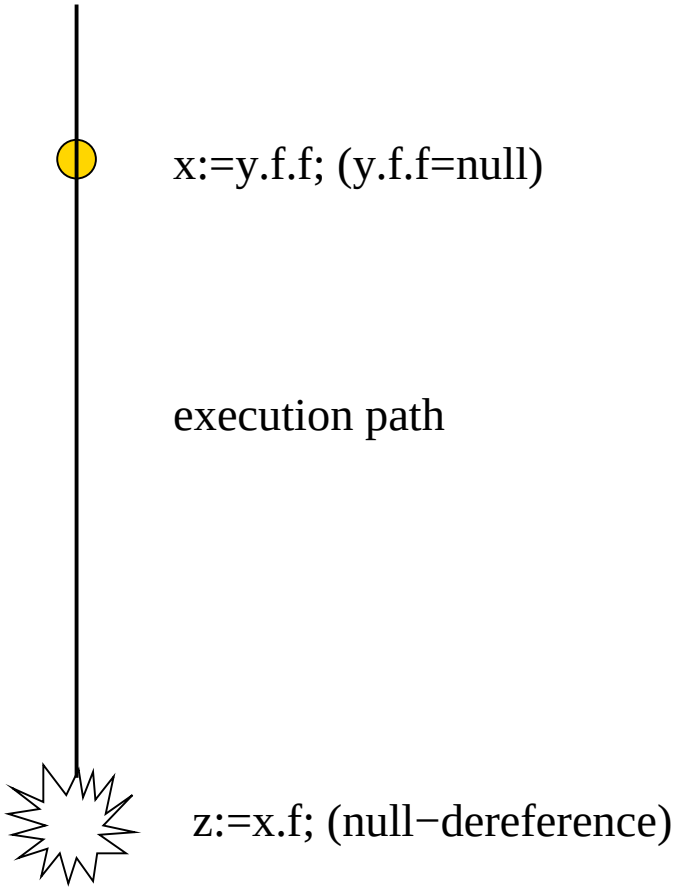

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Locating a Bug by Iterative Execution

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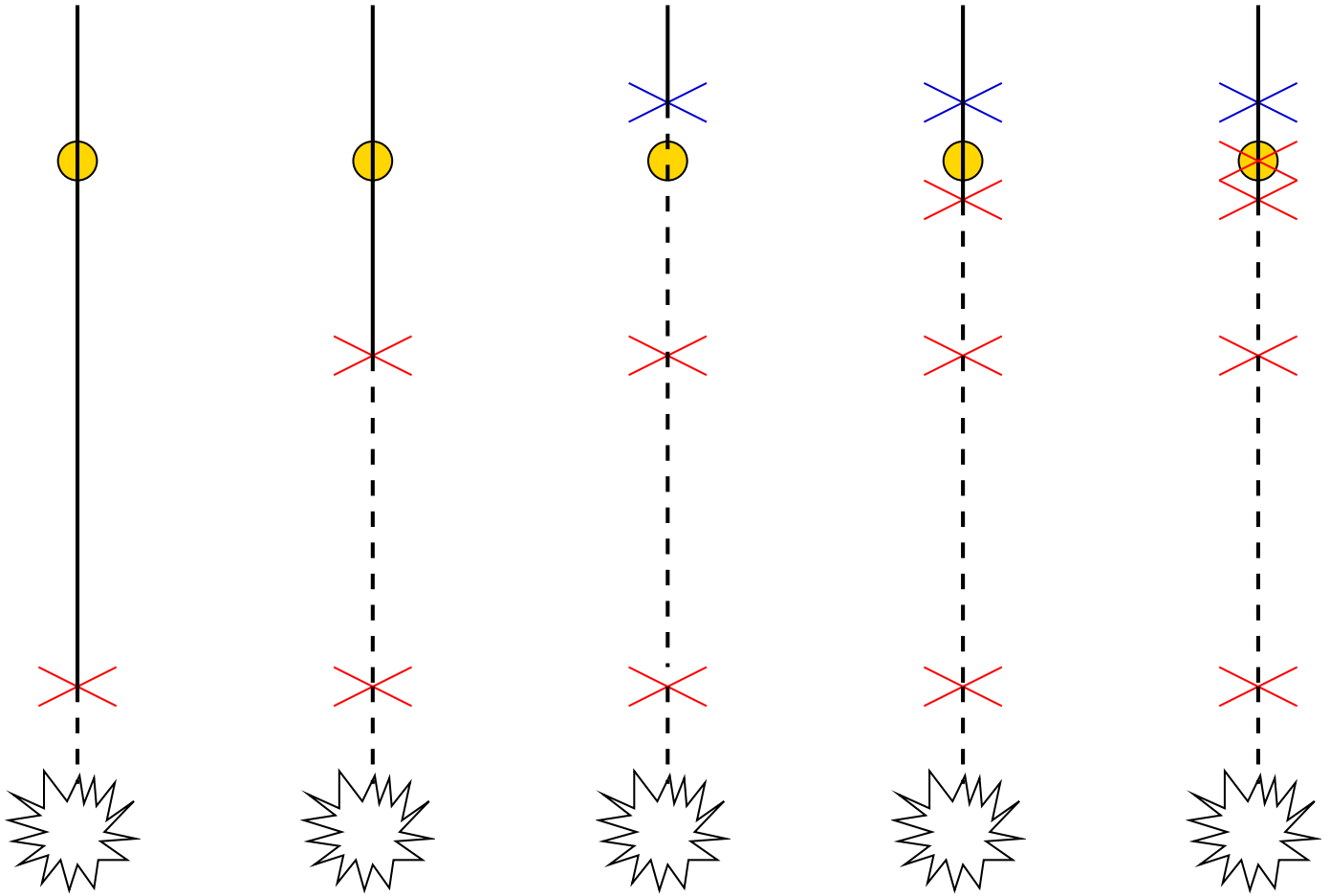
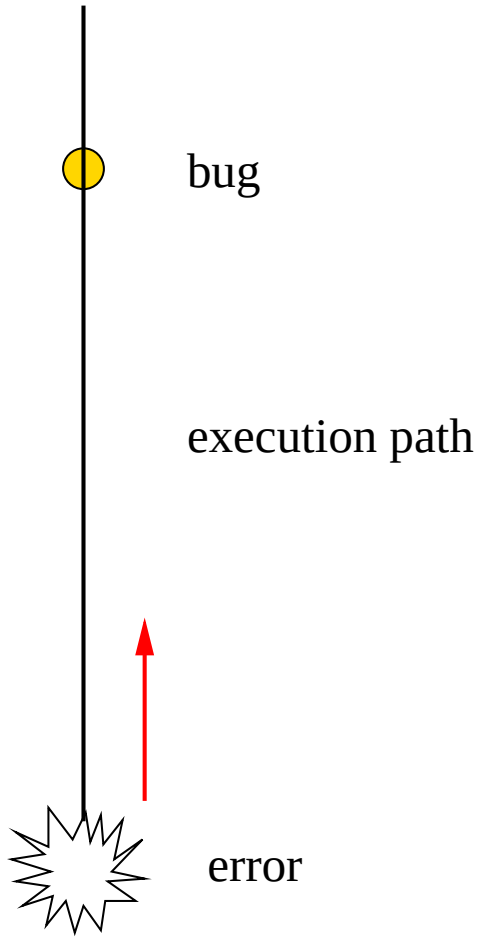


Locating a Bug by Reverse Execution

- As an alternative, reverse execution has been suggested
- Functionally similar to undo in text editors



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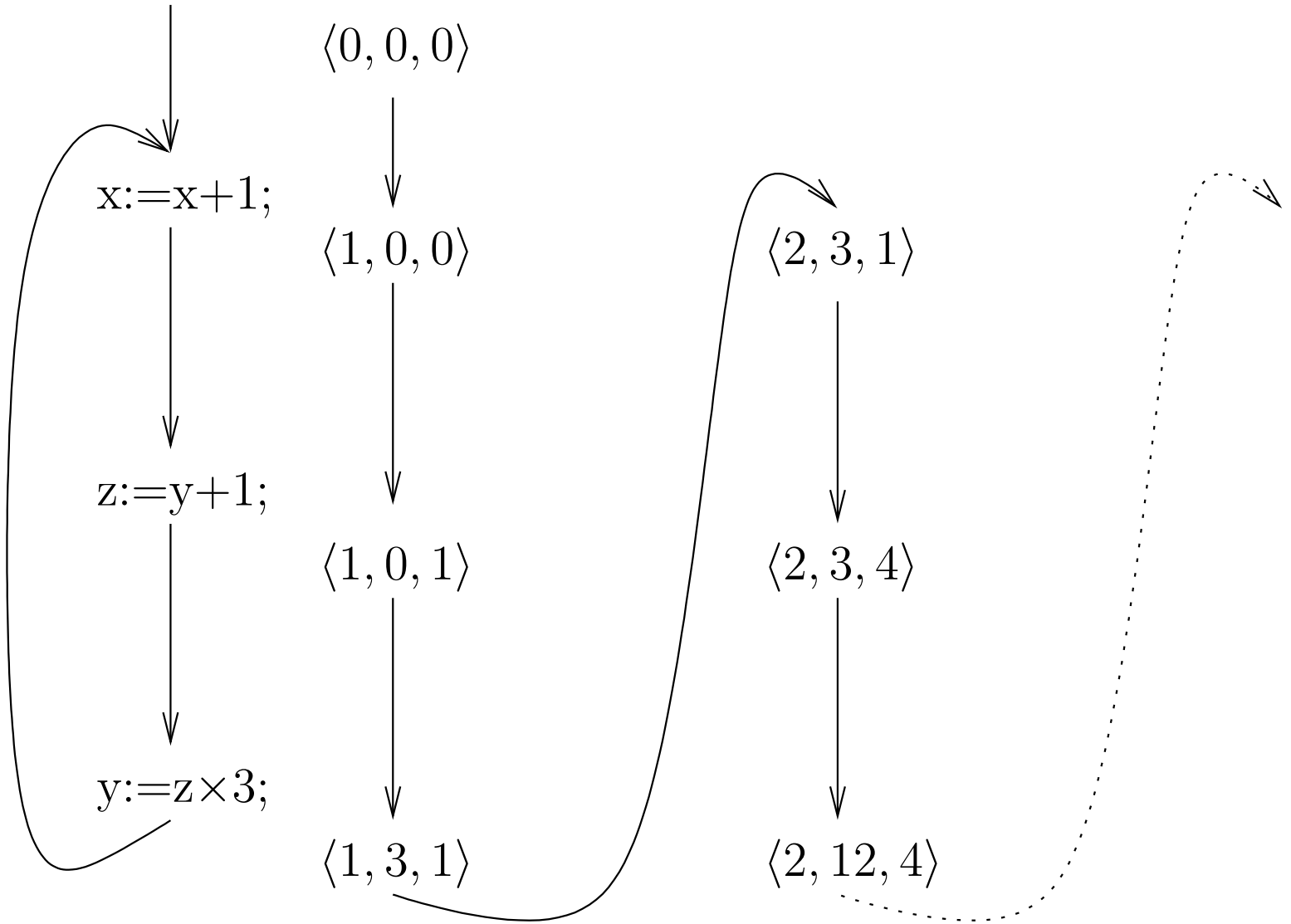
Program Verification by Symbolic Execution

In the literature:

- State-Saving
- Checkpointing
- Reverse Code

Loop Example



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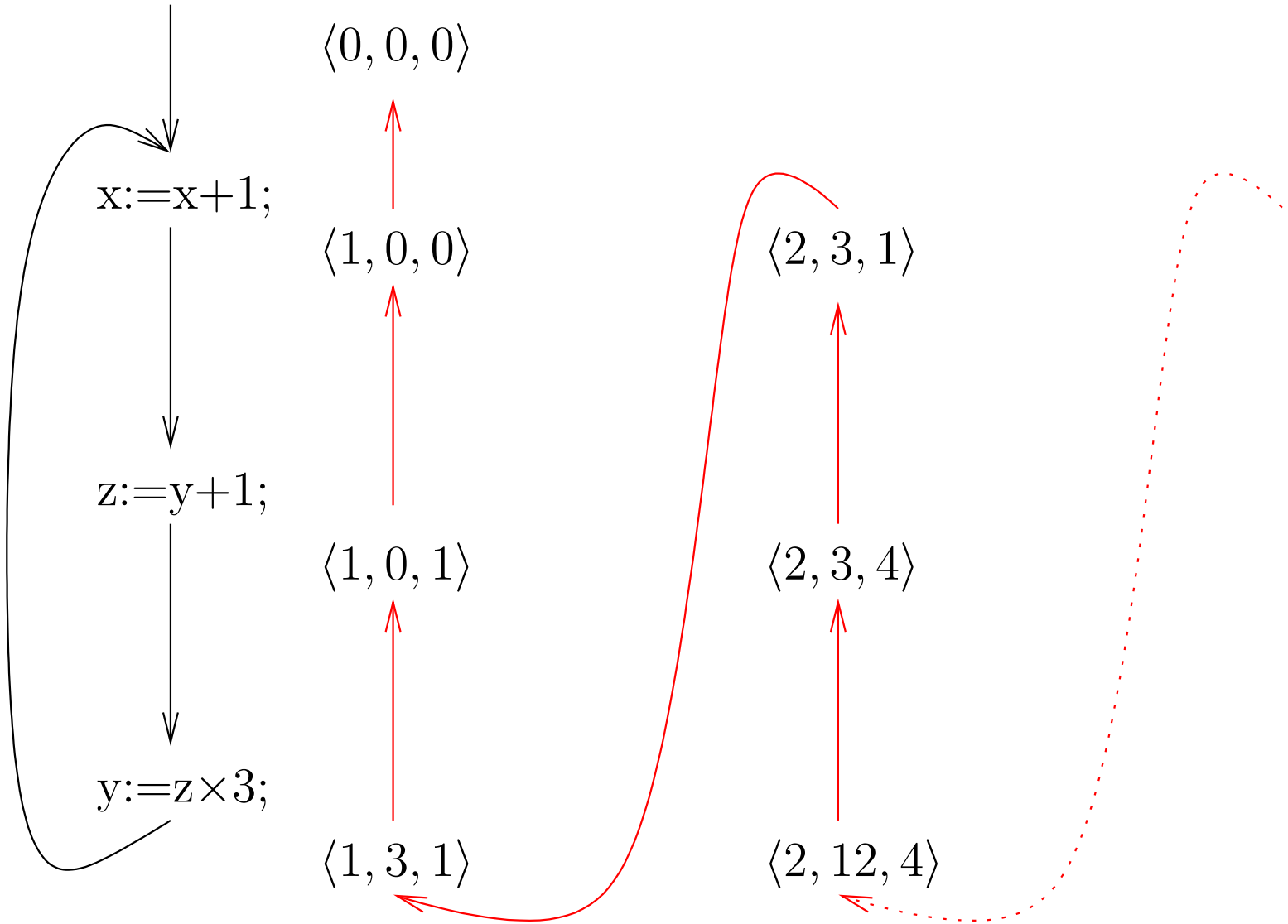

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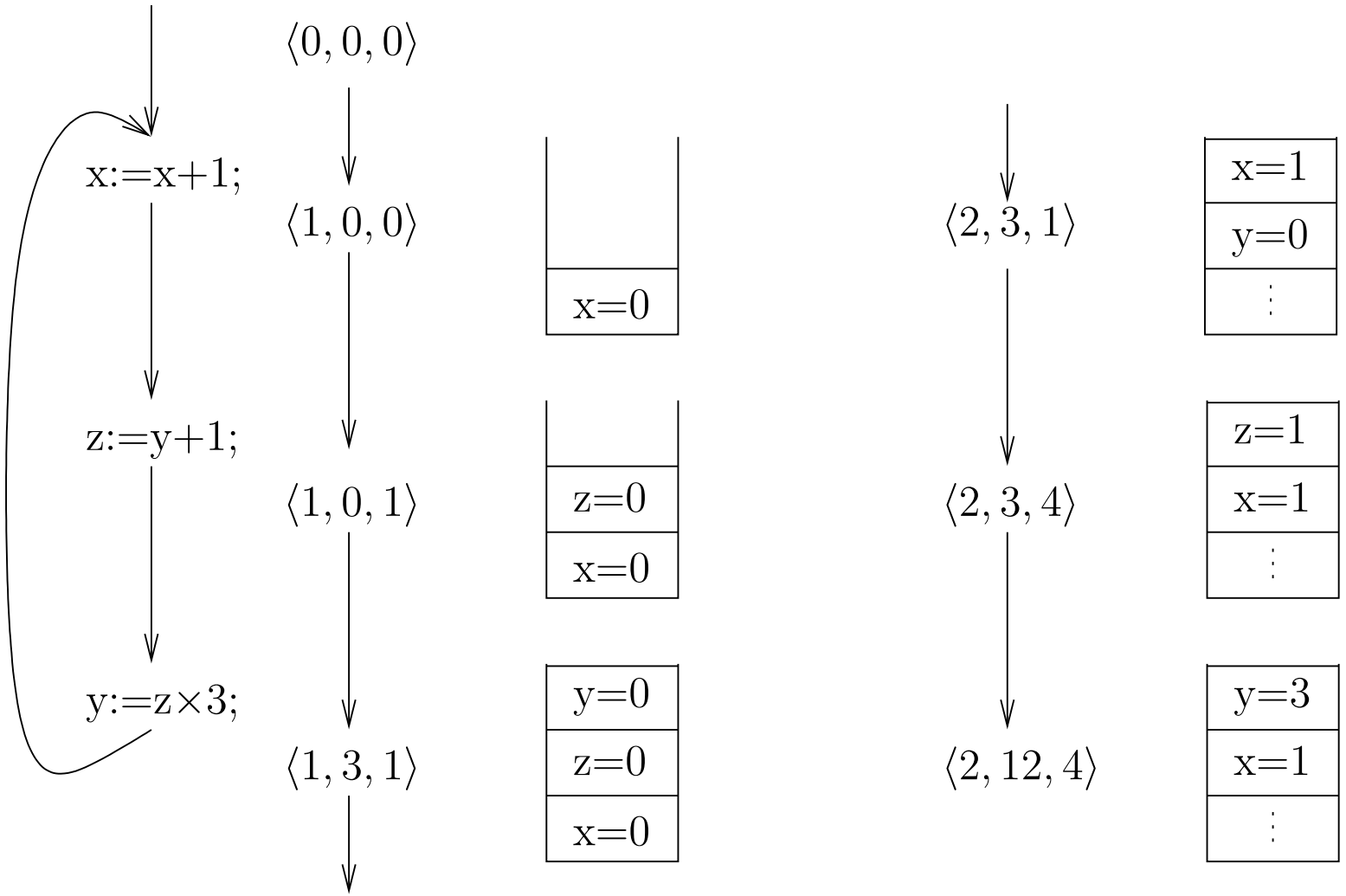

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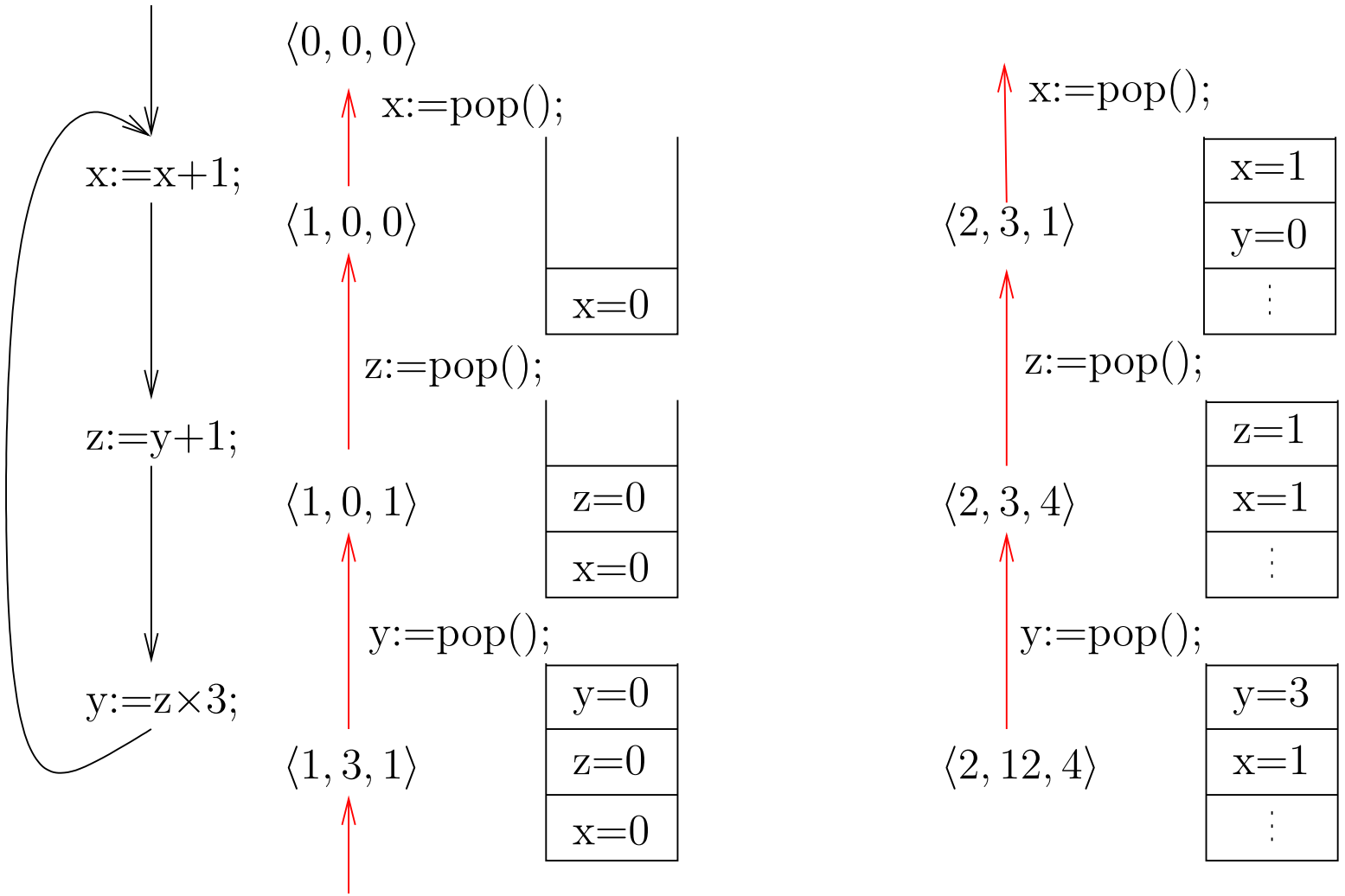

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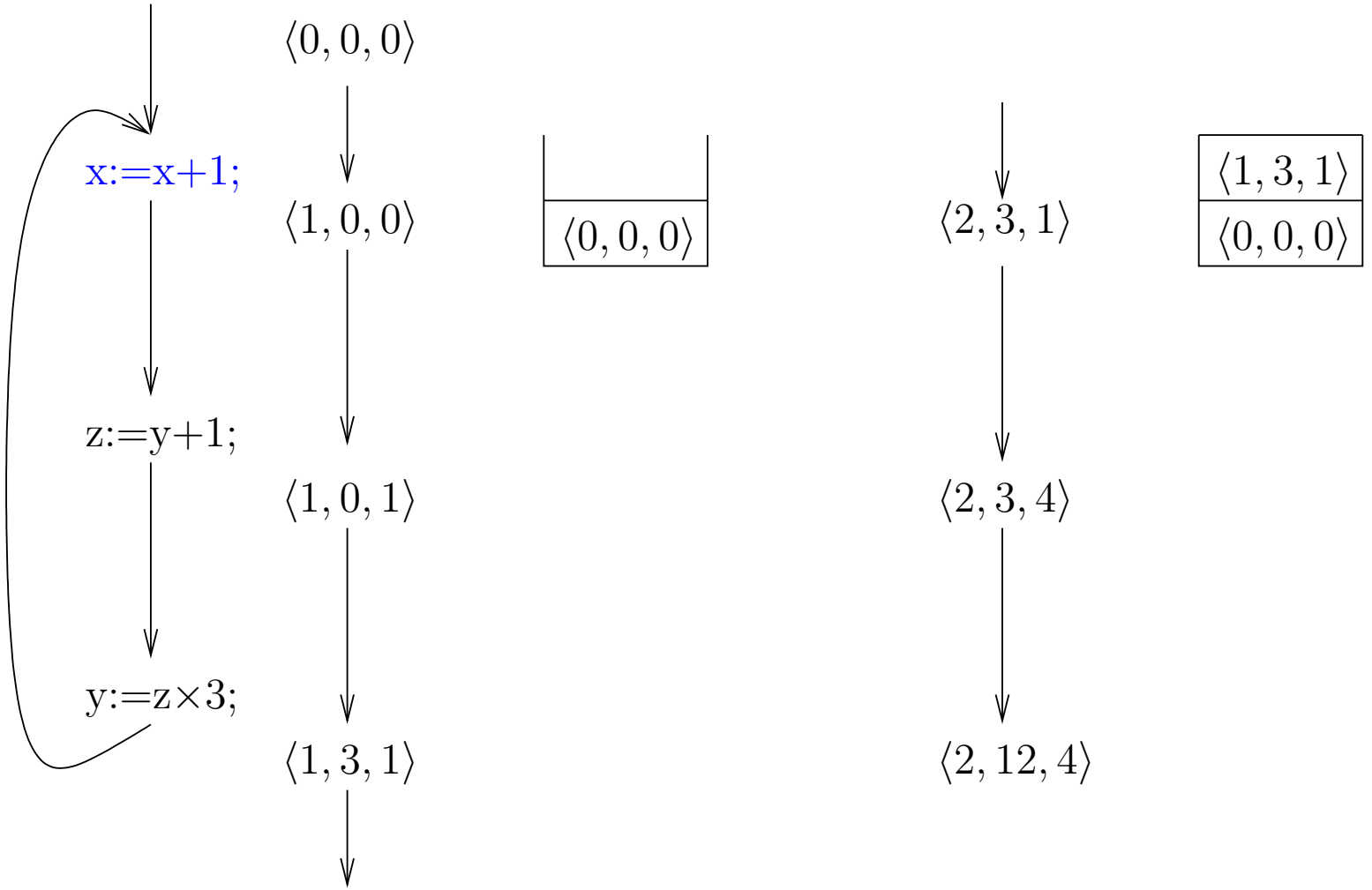
Program Verification by Symbolic Execution

■ Periodic state-saving



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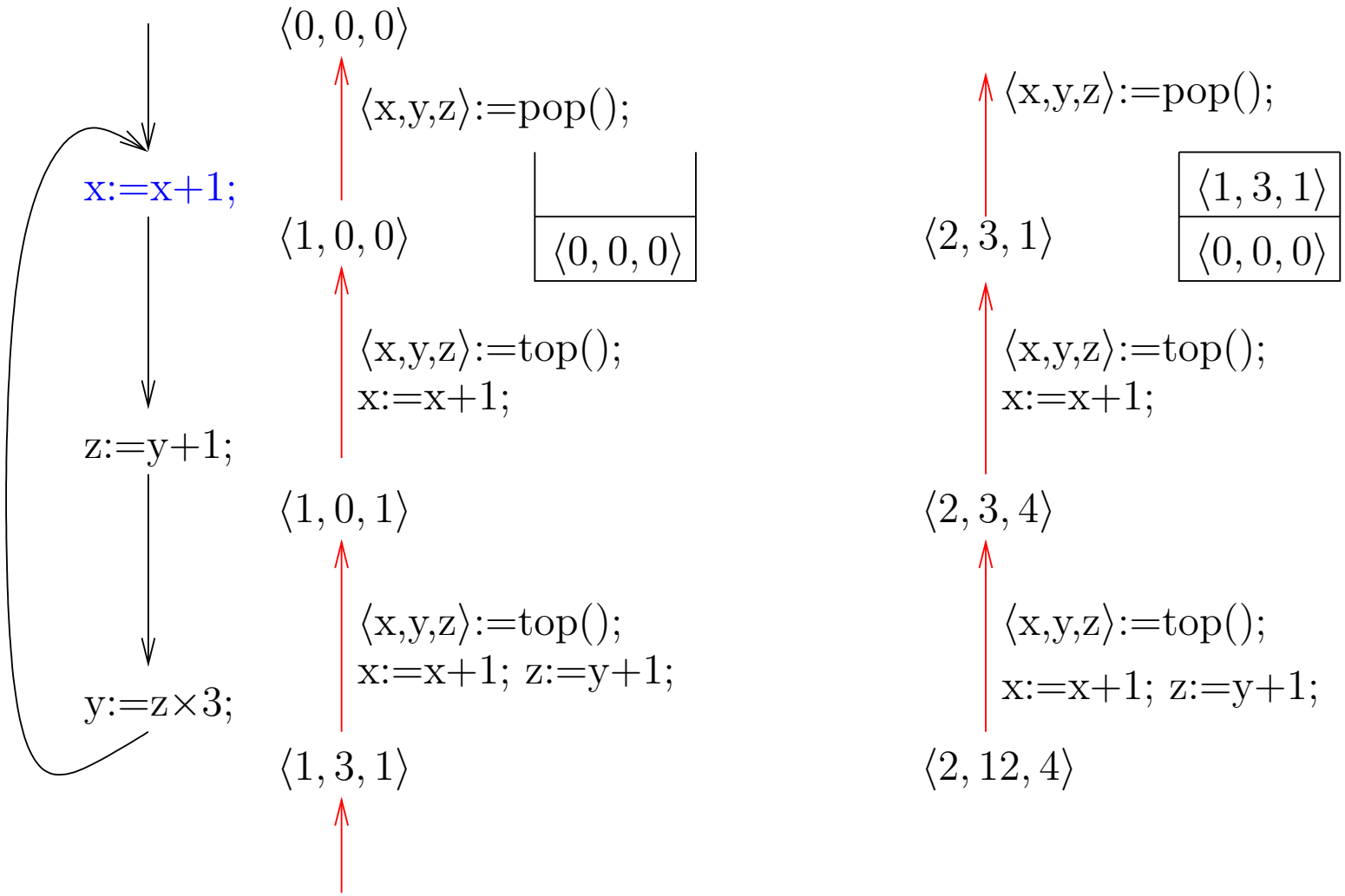
Periodic state-saving



Reverse Execution by Checkpointing

- Periodic state-saving
- It consumes fewer stack elements than state-saving if. . .
- State-saving and checkpointing depend heavily on the use of the stack
- The stack is usually allocated in the memory of a computer

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Reverse Execution by Reverse Code

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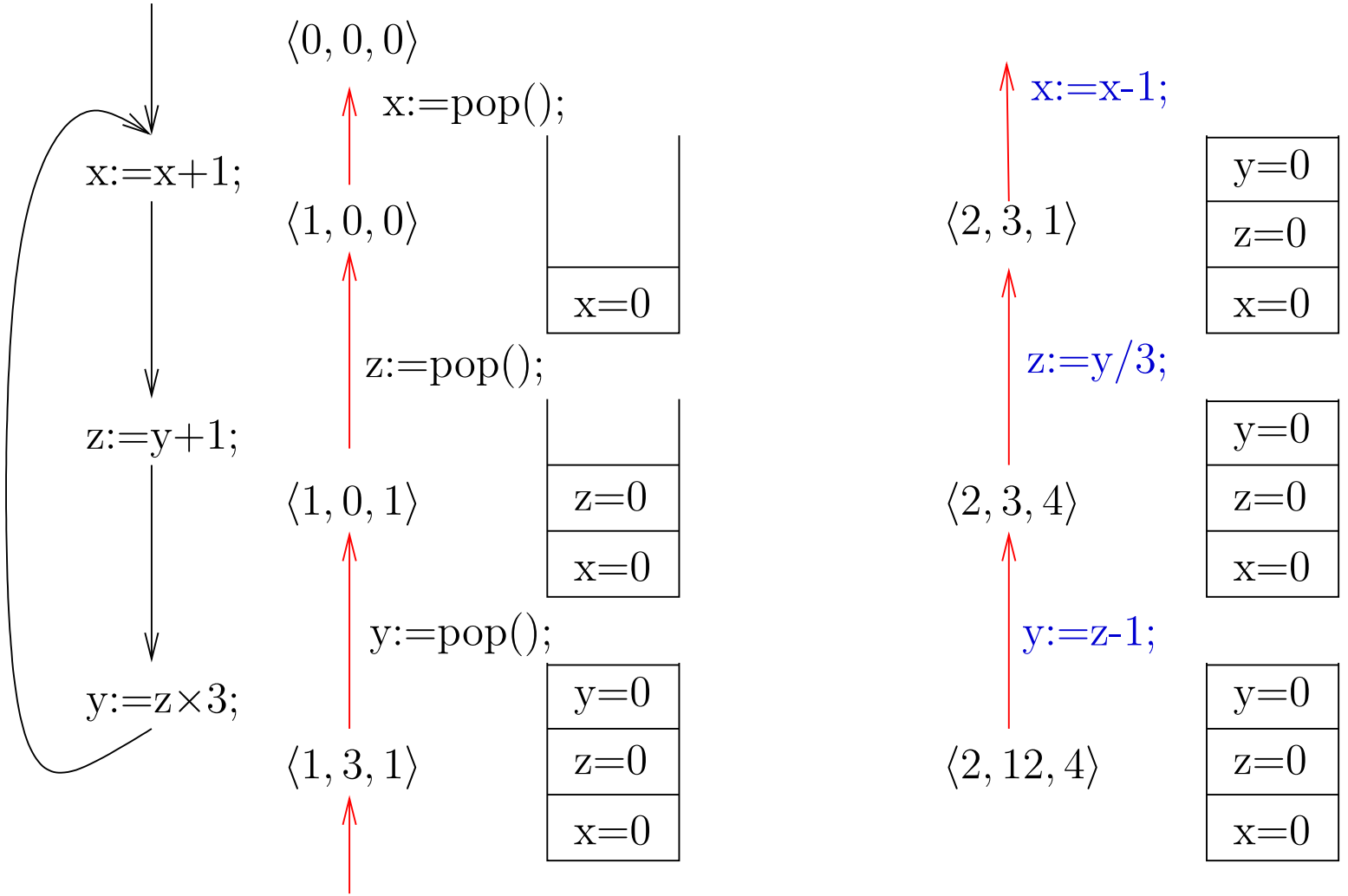
Program Validation by Symbolic Execution

- Reverse code alleviates the situation



Reverse Code Generation

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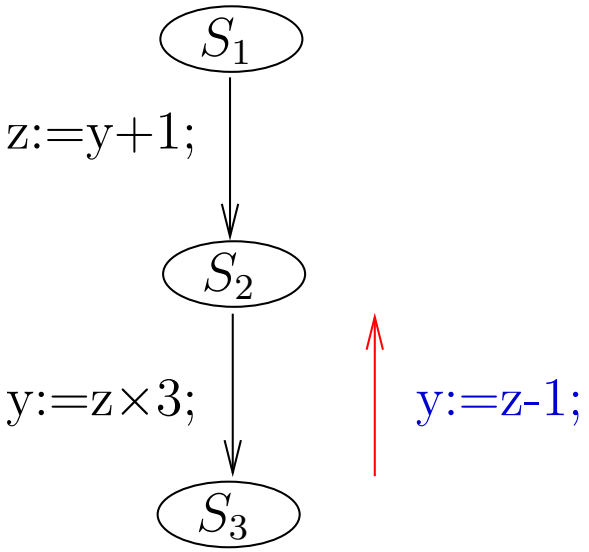
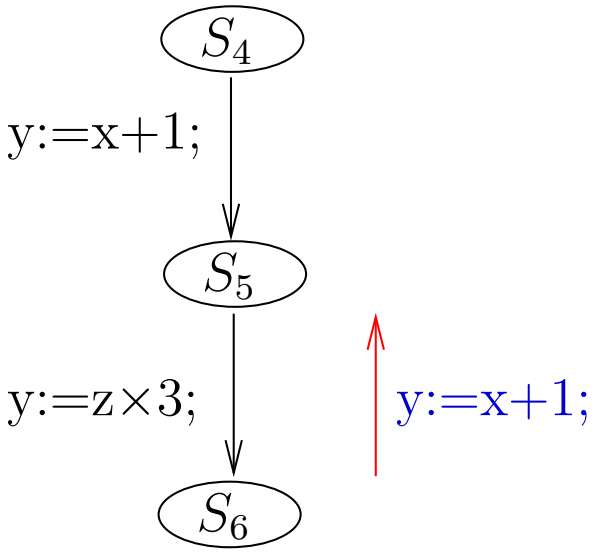
Program Validation by Symbolic Execution

- Extraction-from-use



- y was used in z:=y+1;.
- z=$(\lambda t.t+1)$(y)
- y=$(\lambda t.t+1)^{-1}$(z)
- $(\lambda t.t+1)^{-1}$=$(\lambda t.t-1)$
- y=$(\lambda t.t-1)$(z)
- y:=z-1;.

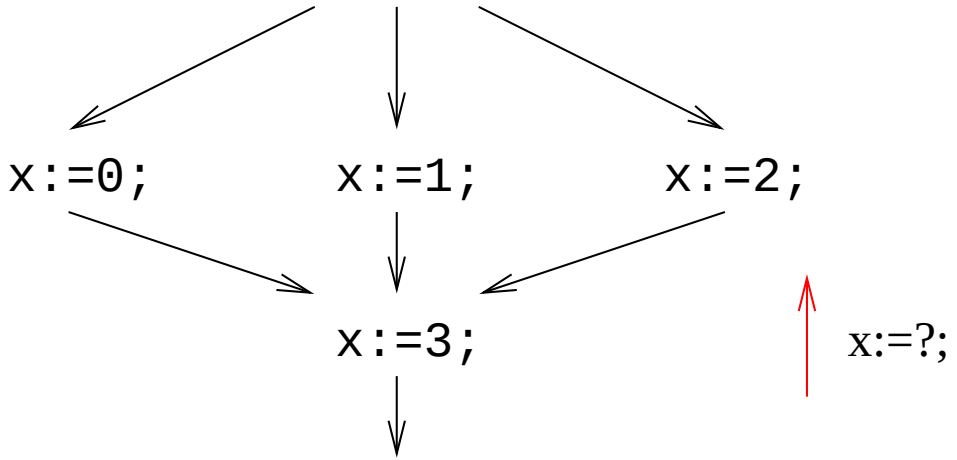
- Redefinition



- y:=x+1; is a reaching definition of y.

Static Reverse Code Generation

- shown in [Akgul and Mooney, PASTE'02]
- Analyzes a source program
- Before executing a program
- Infeasible for non-deterministic programs



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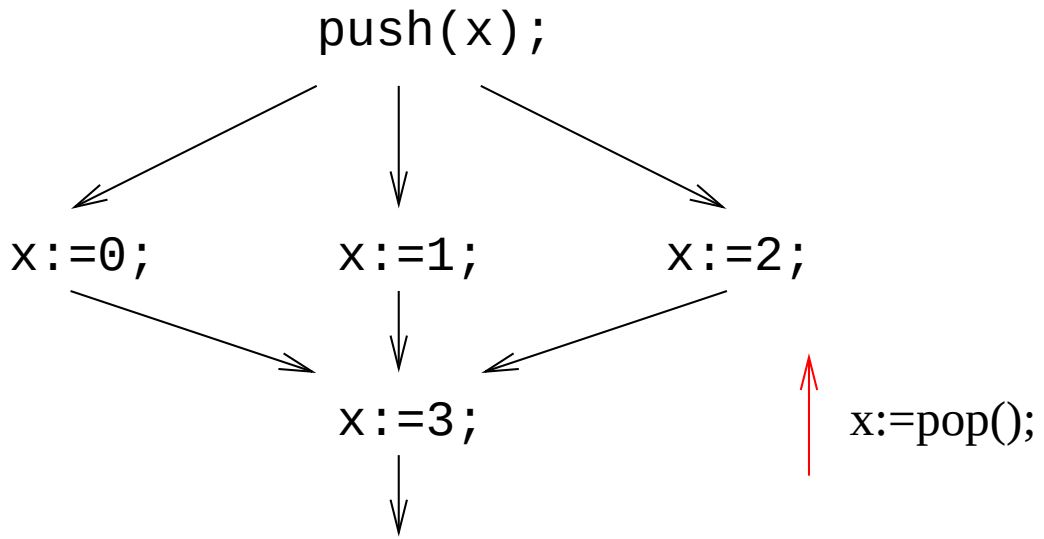

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Program Validation by Symbolic Execution

- shown in [Akgul and Mooney, PASTE'02]
- Analyzes a source program
- Before executing a program
- Infeasible for non-deterministic programs

- Does it matter?

Static Reverse Code Generation

- shown in [Akgul and Mooney, PASTE'02]
- Analyzes a source program
- Before executing a program
- Infeasible for non-deterministic programs

- Does it matter?

Yes, it does!

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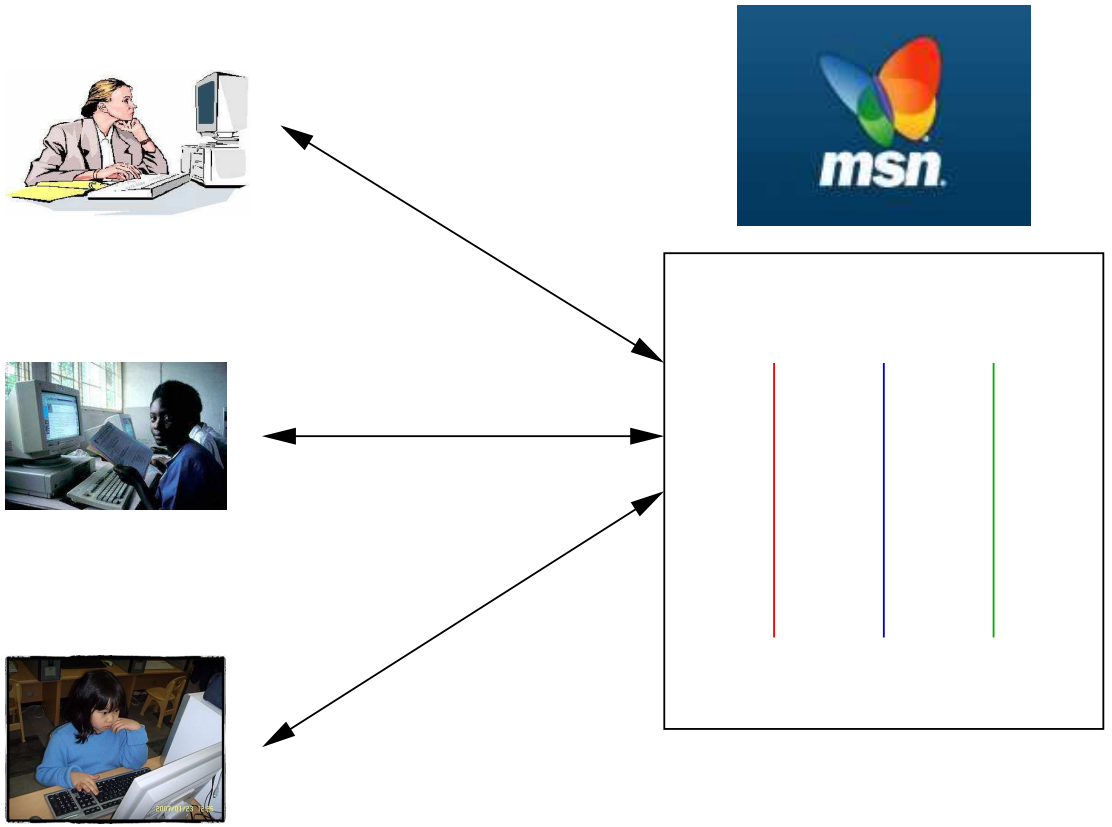
Multi-threaded Programs

- Multi-threaded programs occur everywhere.
- They are non-deterministic.



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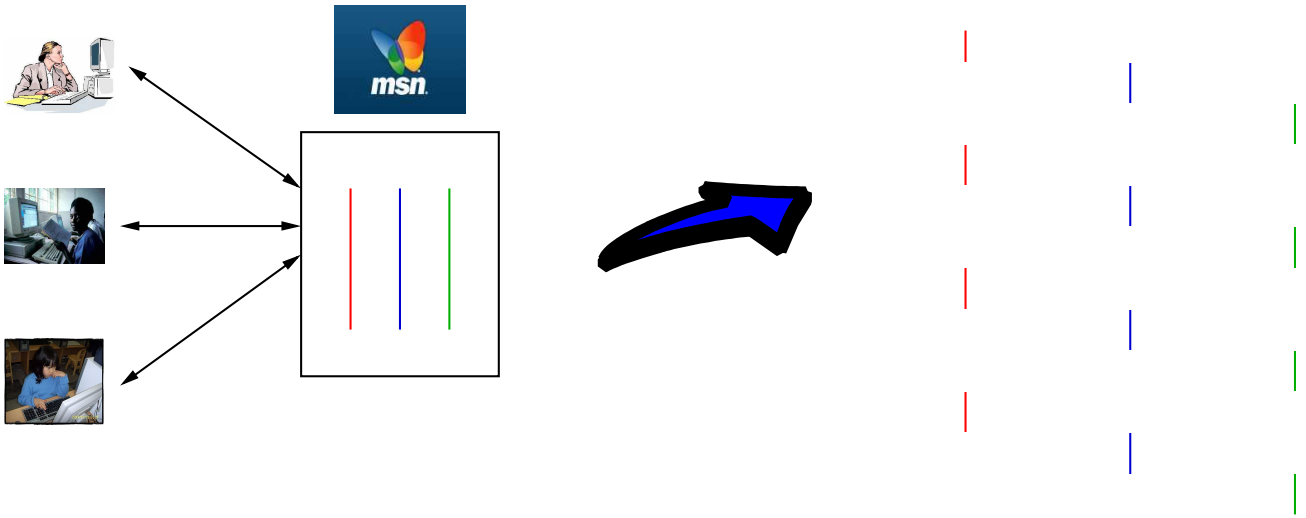
Multi-threaded Programs

- Multi-threaded programs occur everywhere.
- They are non-deterministic.
- Interleaving



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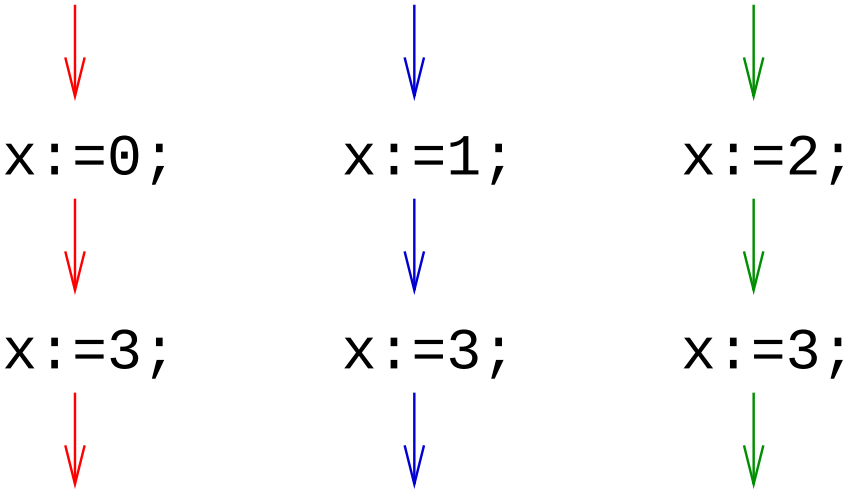

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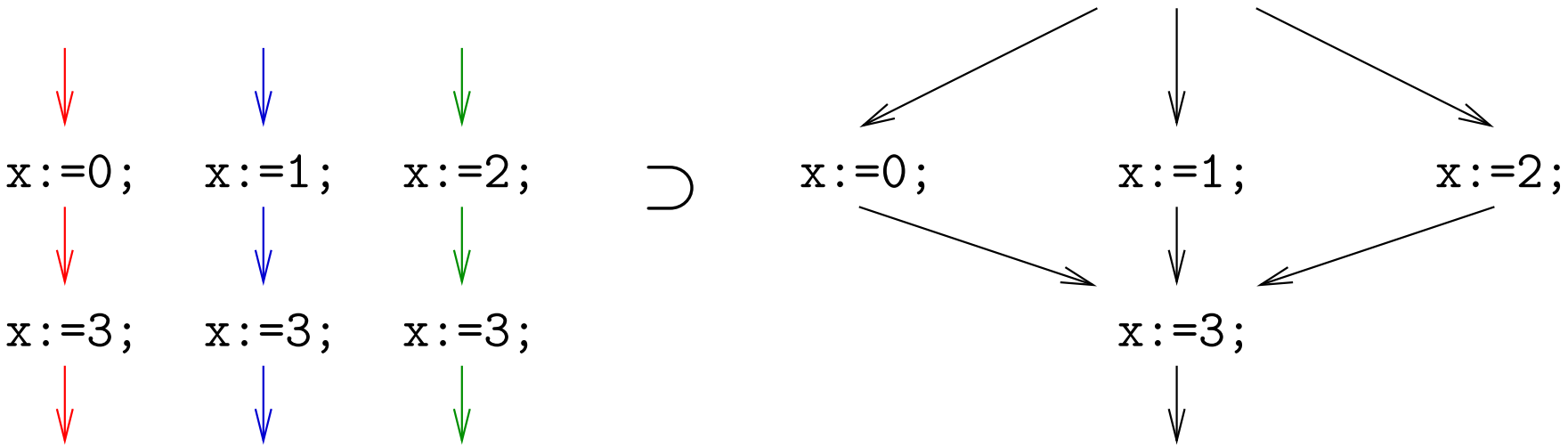
Multi-threaded Programs

- Multi-threaded programs occur everywhere.
- They are non-deterministic.
- Interleaving $\Rightarrow$ Non-determinism



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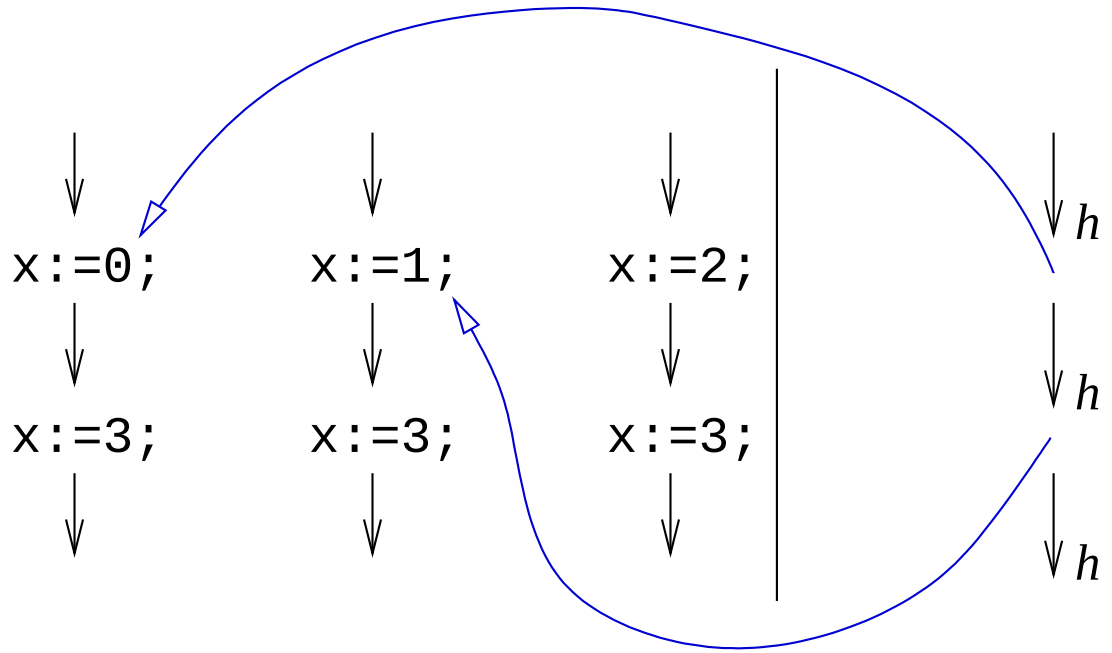
Program Validation by Symbolic Execution

Dynamic Reverse Code Generation

- proposed in [Lee, V&D'06] and Chapter 5 of the dissertation
- Scales to multi-threaded programs
- Analyzes a runtime history of statements
- On-demand-basis generation at runtime
- A runtime history is essential for the reverse execution in non-deterministic programs, regardless of methods
- There is no way to infer non-deterministic choices



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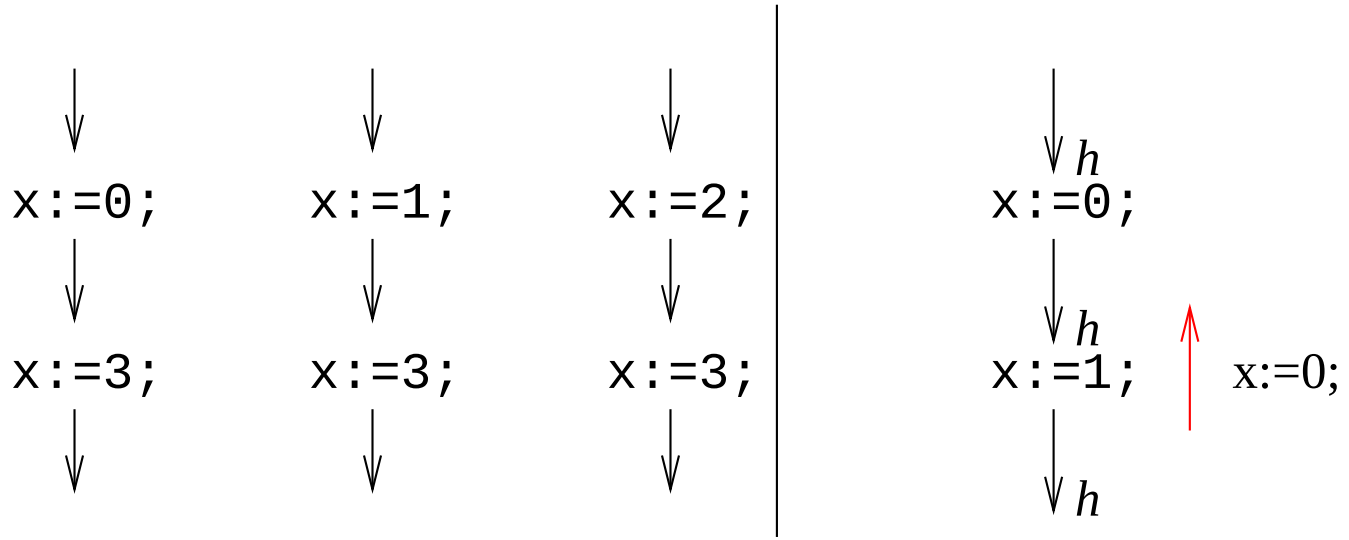

Static vs. Dynamic Reverse Code Generation

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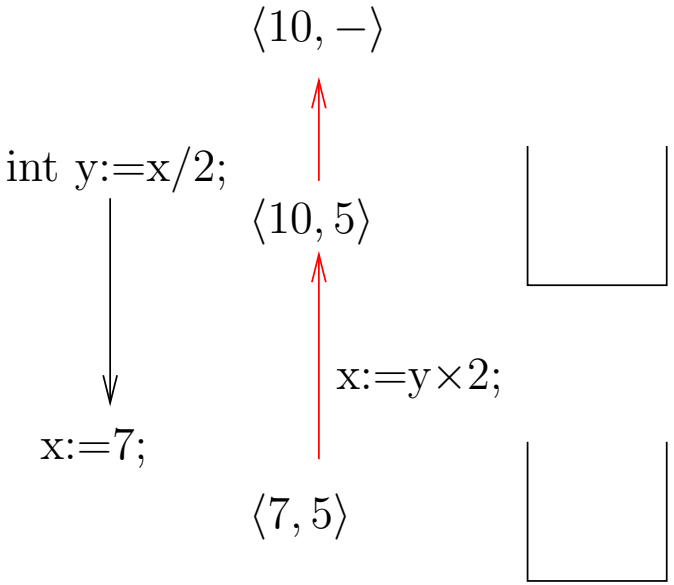
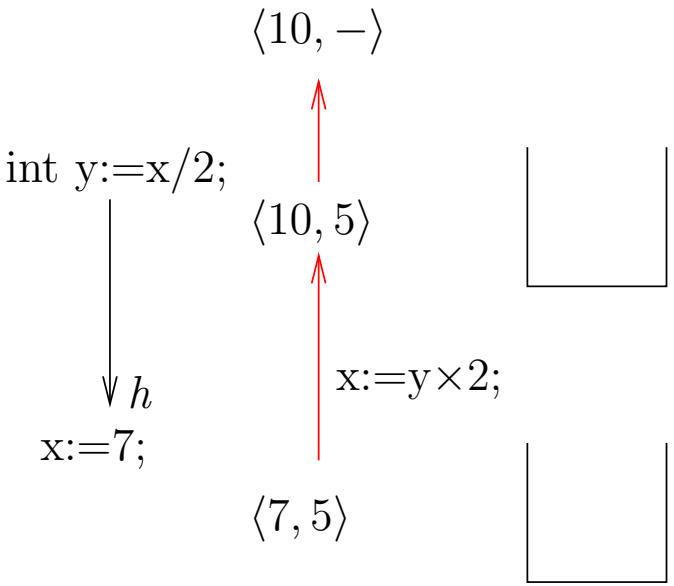
Program Validation by Symbolic Execution

- Source program
- Feasible only for deterministic programs
- Value-insensitive



- Minimal runtime overhead

- Runtime history
- Feasible for non-deterministic programs
- Value-sensitive



- Substantial runtime overhead
  - Multi-core processors
  - Interactive debugging

Static vs. Dynamic Reverse Code Generation

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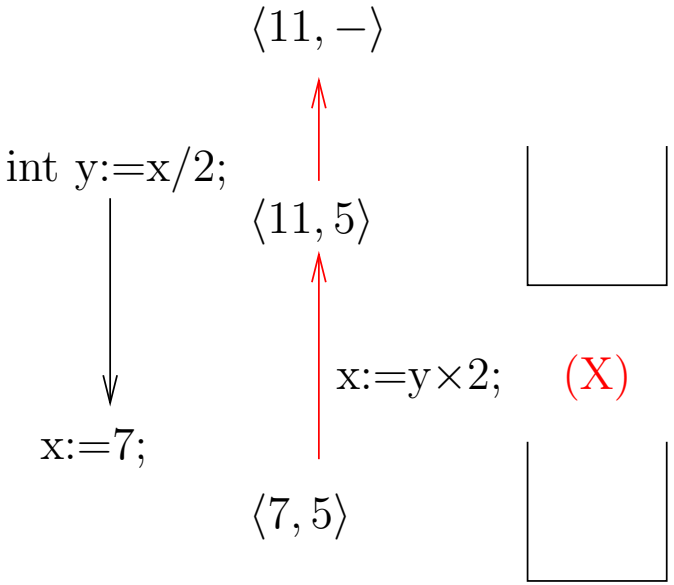

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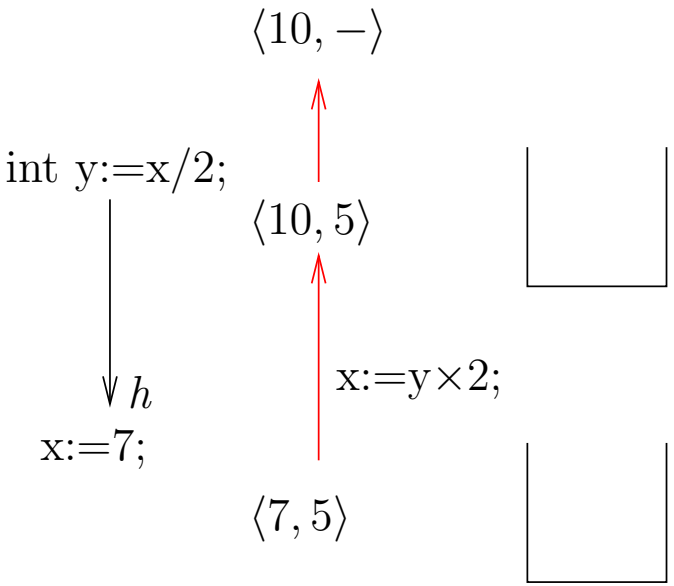

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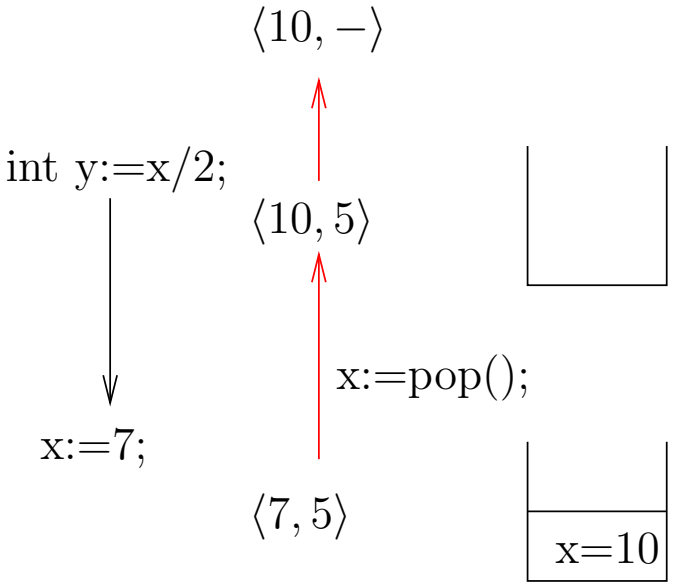

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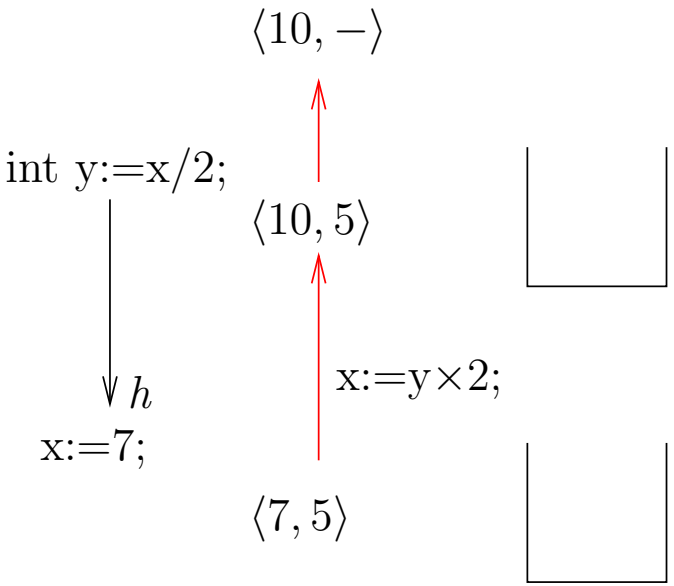

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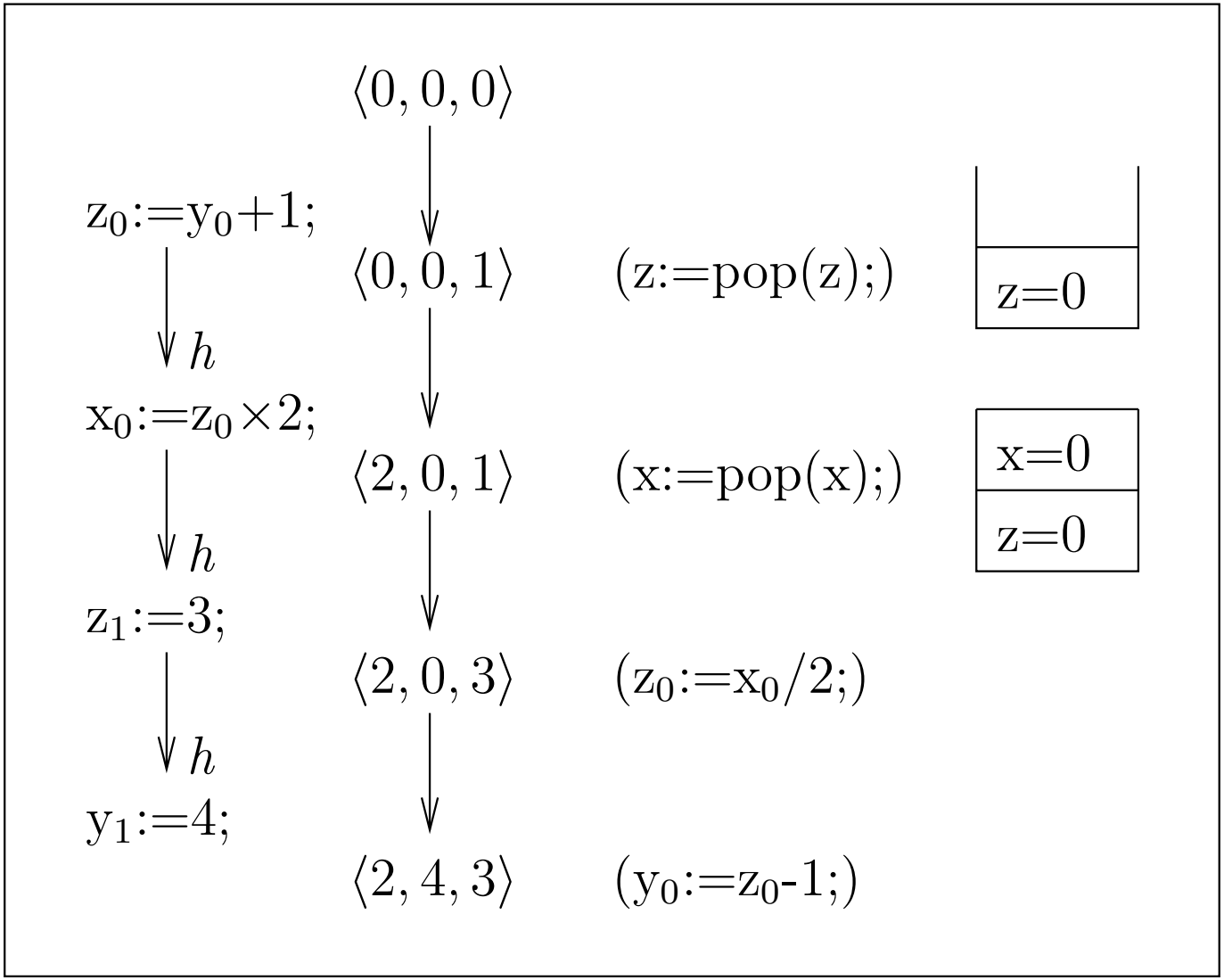
Dynamic Reverse Code Generation



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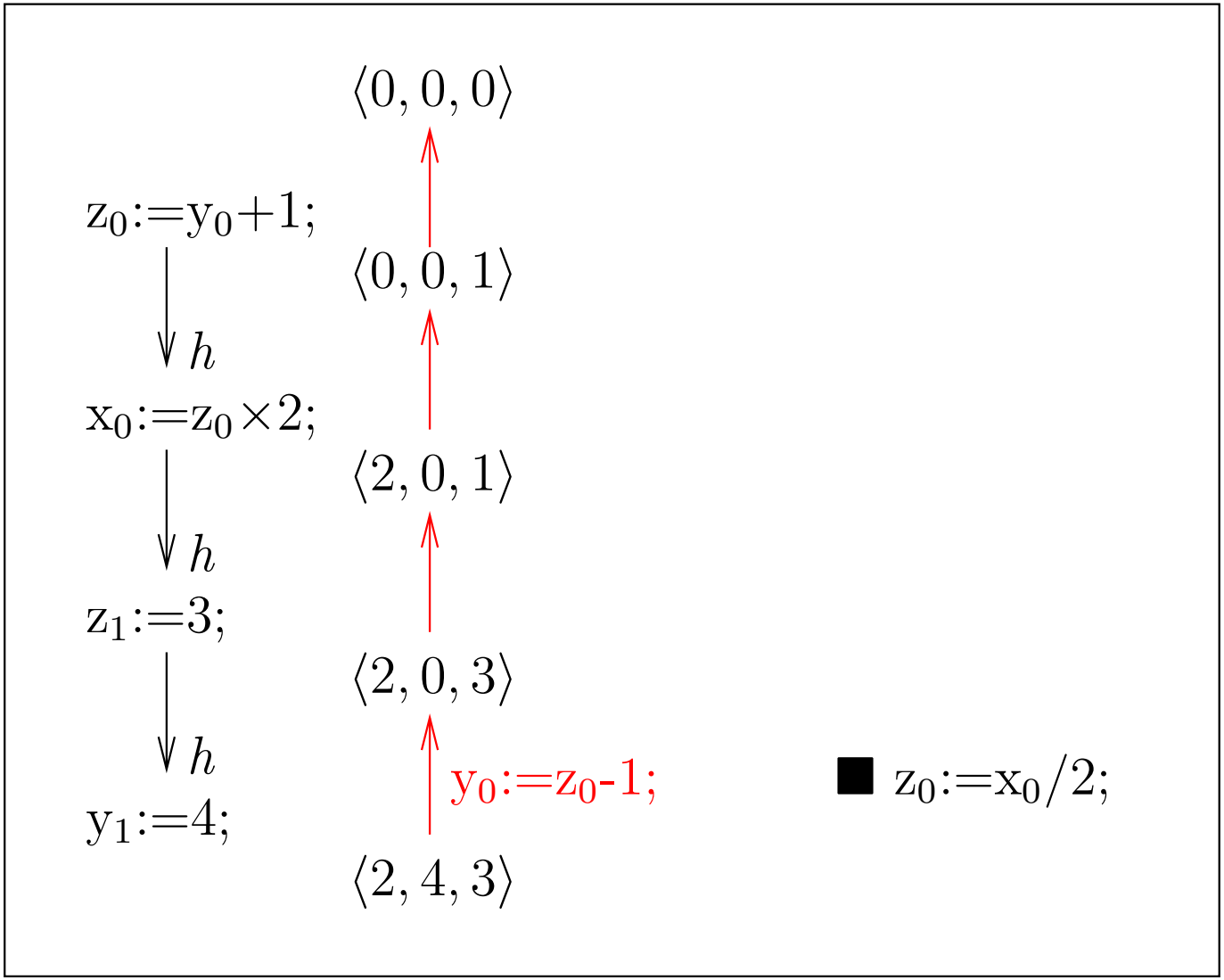

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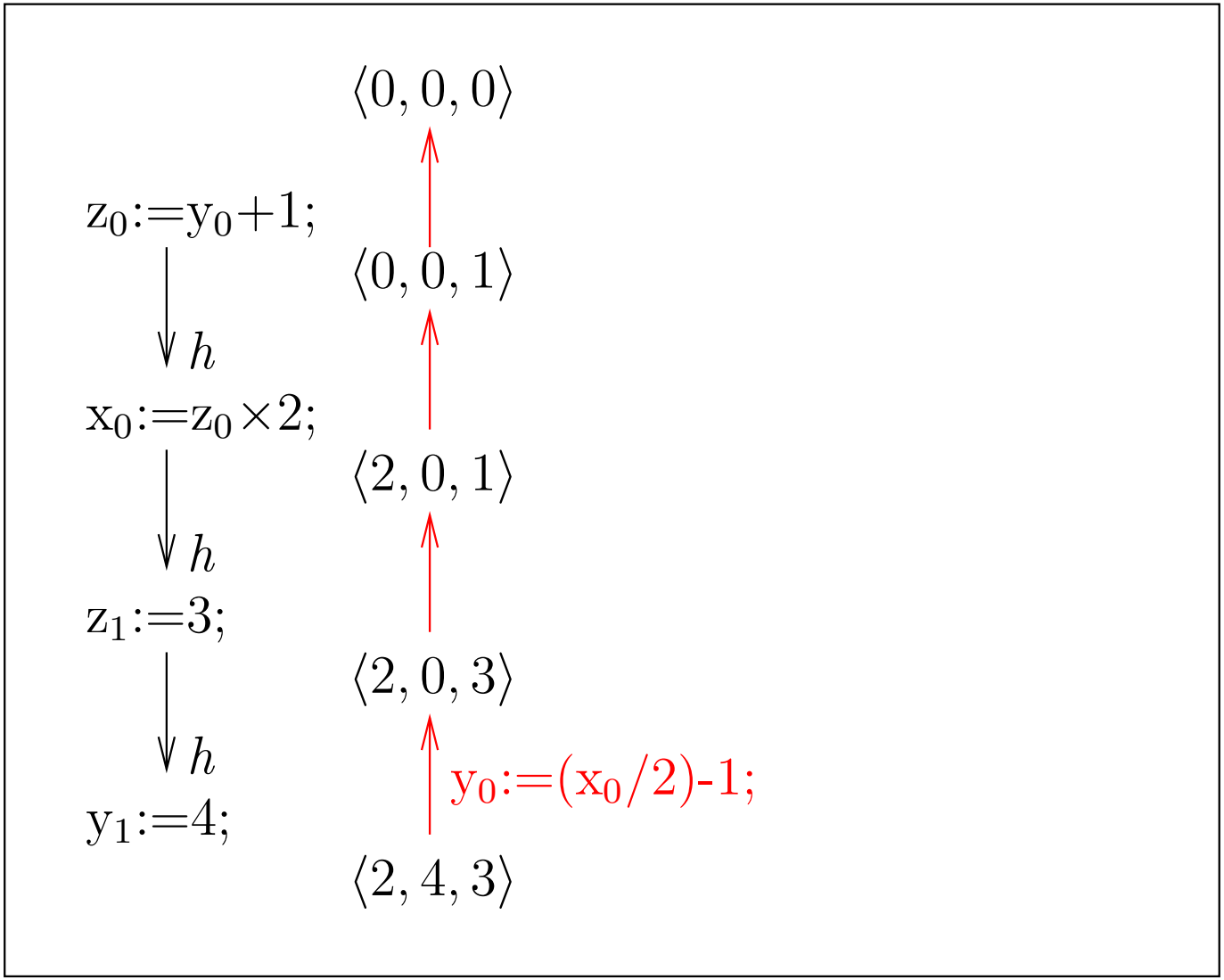

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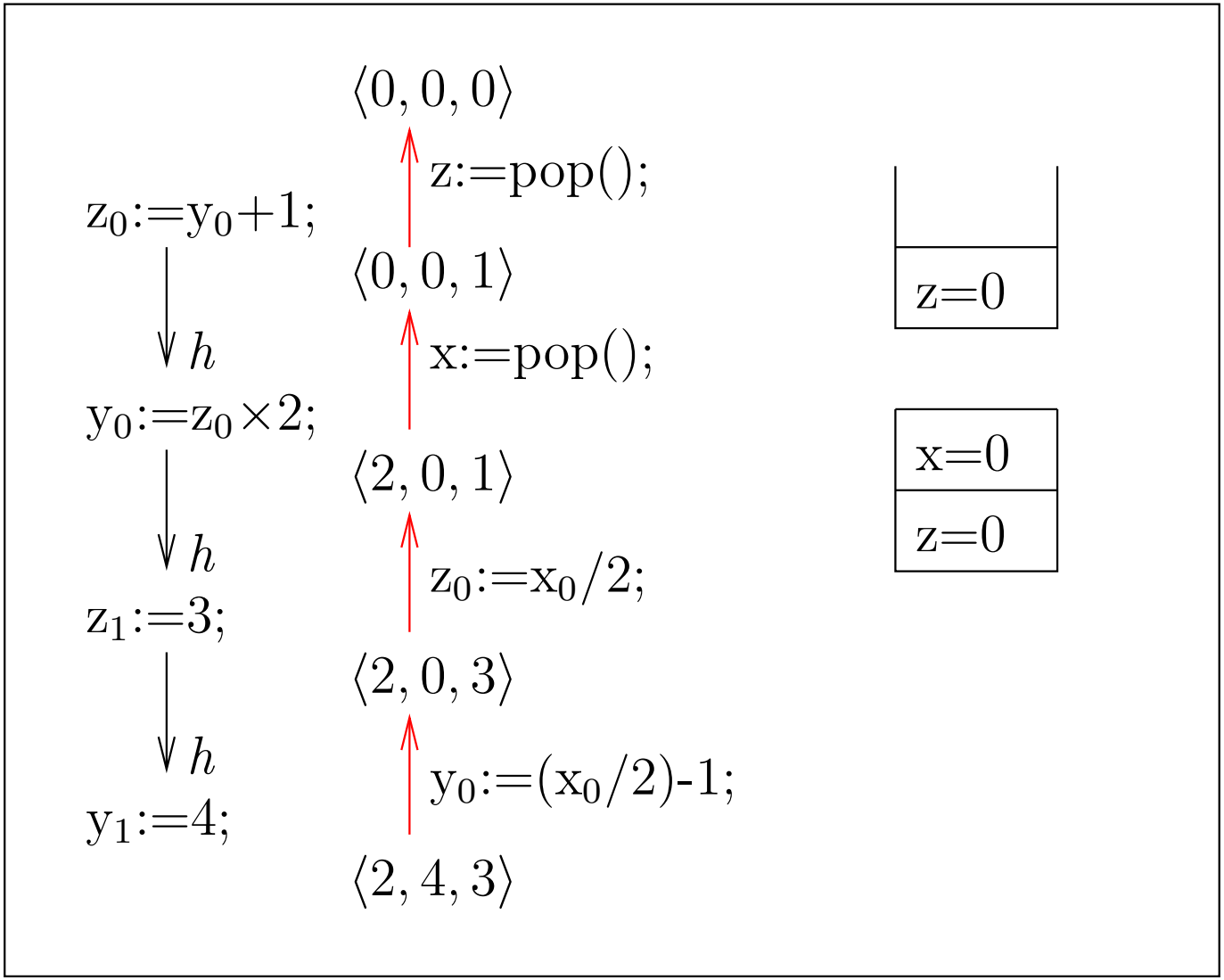

Multiple Variables

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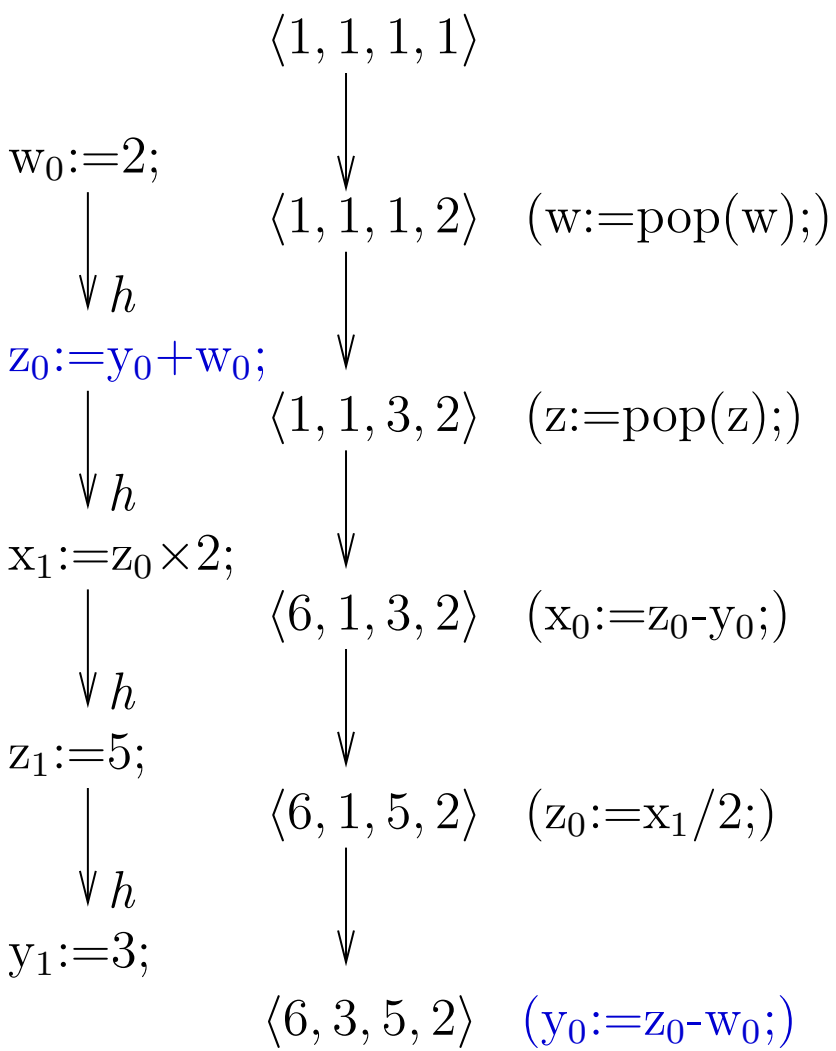

- $z_0=(\lambda t.t+w_0)(y_0)$
- $(\lambda t.t+w_0)^{-1}=(\lambda t.t-w_0)$
- $y_0=(\lambda t.t-w_0)(z_0)$

Multiple Variables

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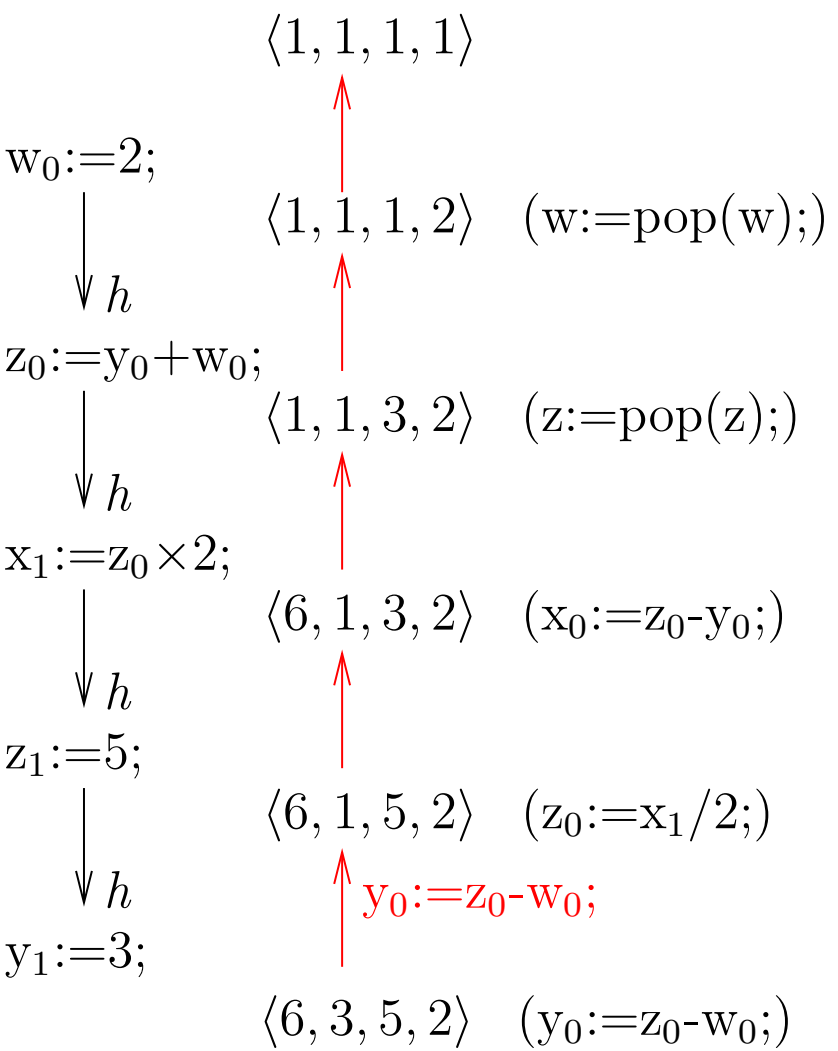

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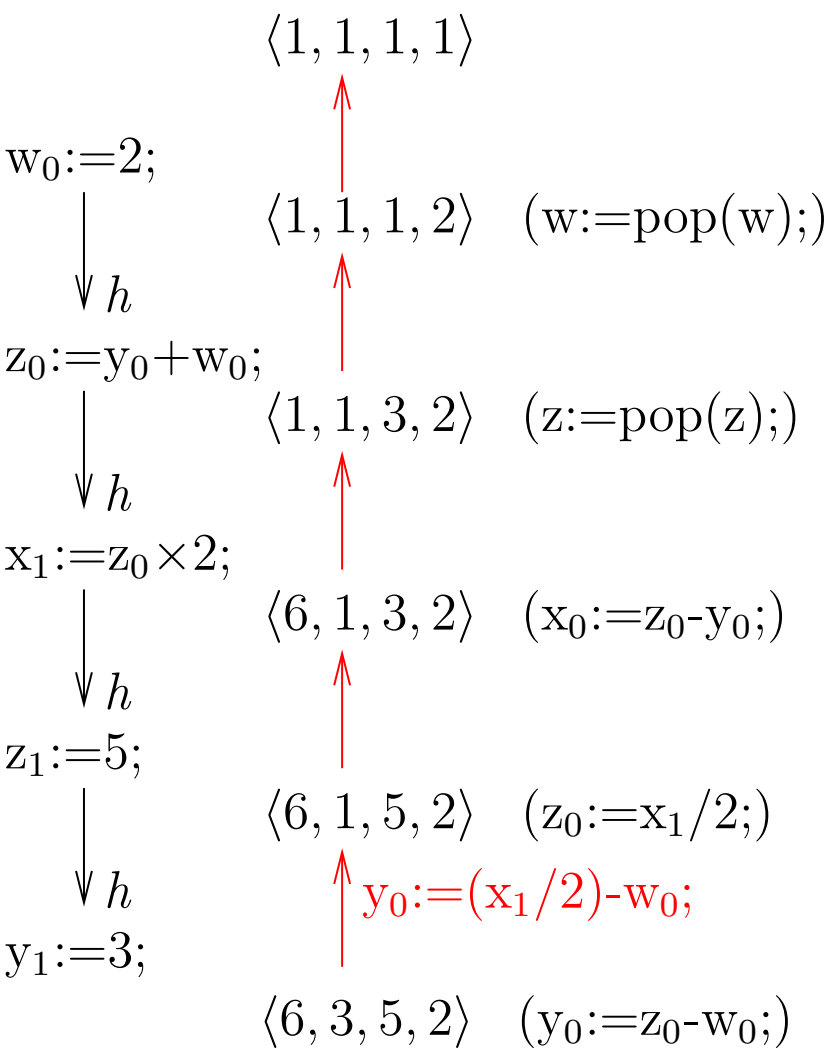
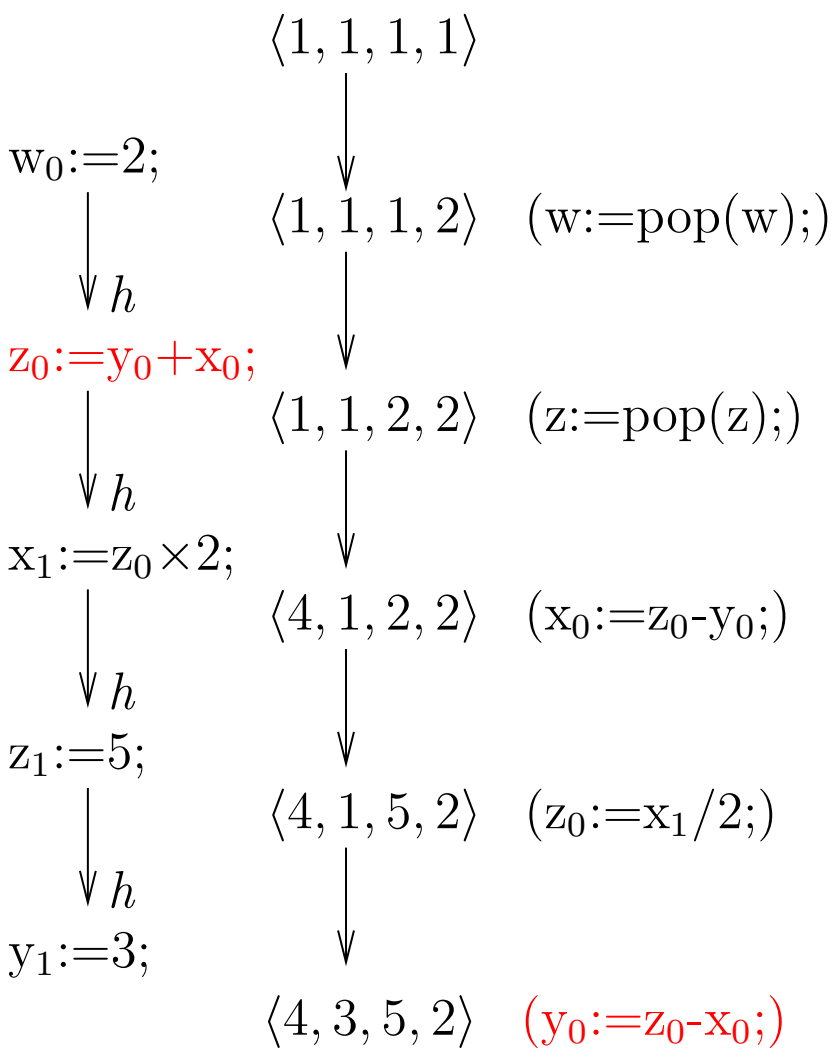


Multiple Variables



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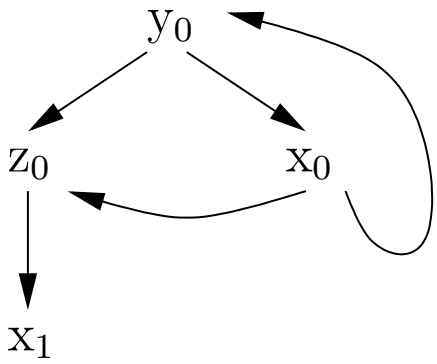
Program Validation by Symbolic Execution

$$
\begin{array}{ll}
 & \langle 1,1,1,1\rangle \\
 & \uparrow \\
w_0{:=}2; & \\
\downarrow h & \\
 & \langle 1,1,1,2\rangle \quad (w{:=}pop(w);) \\
 & \uparrow \\
z_0{:=}y_0{+}x_0; & \\
\downarrow h & \\
 & \langle 1,1,2,2\rangle \quad (z{:=}pop(z);) \\
 & \uparrow \\
x_1{:=}z_0{\times}2; & \\
\downarrow h & \\
 & \langle 4,1,2,2\rangle \quad (x_0{:=}z_0\text{-}y_0;) \\
 & \uparrow \\
z_1{:=}5; & \\
\downarrow h & \\
 & \langle 4,1,5,2\rangle \quad (z_0{:=}x_1/2;) \\
 & \uparrow \\
\downarrow h & \quad y_0{:=}(x_1/2)\text{-}(z_0\text{-}y_0); \\
y_1{:=}3; & \\
 & \langle 4,3,5,2\rangle \quad (y_0{:=}z_0\text{-}x_0;)
\end{array}
$$



Multiple Variables

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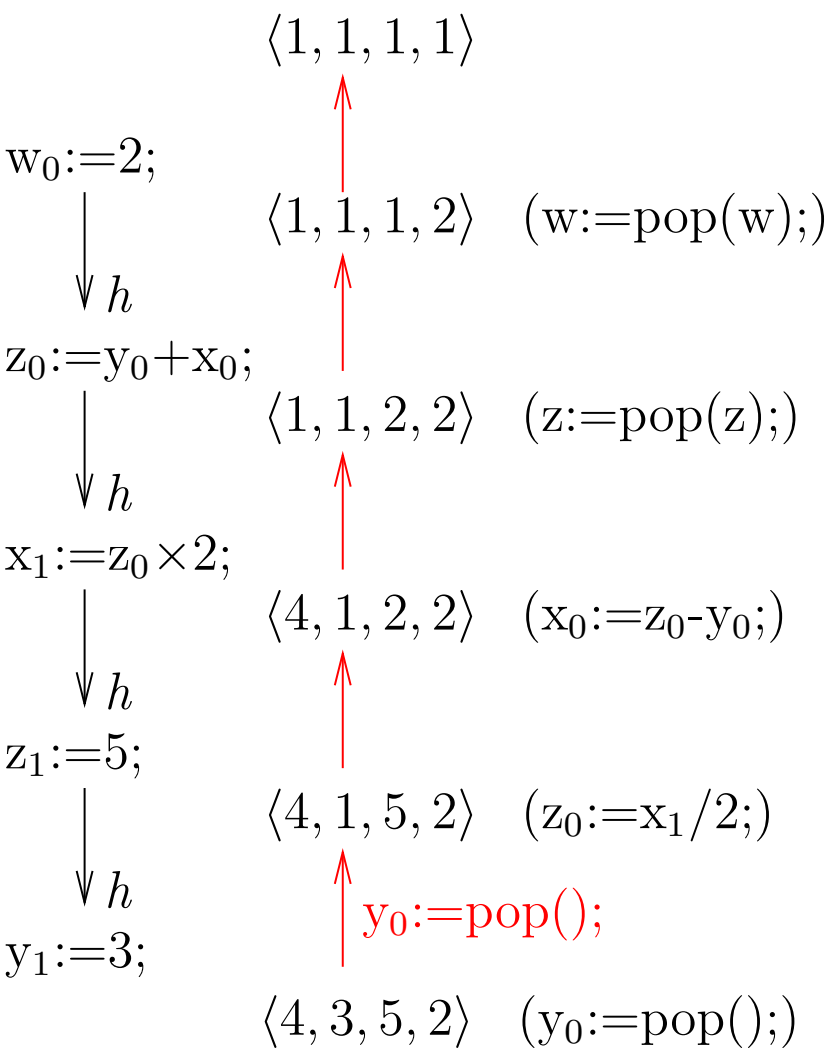
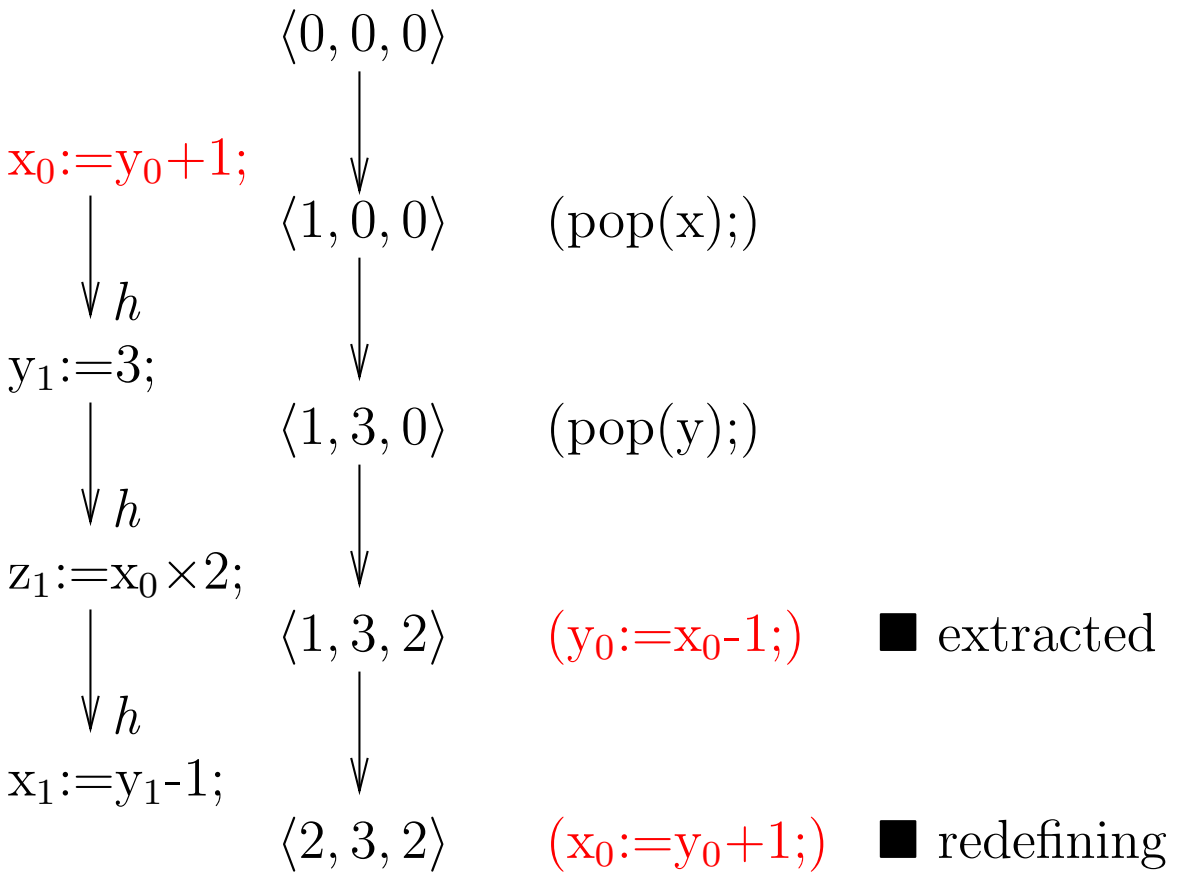


Combination



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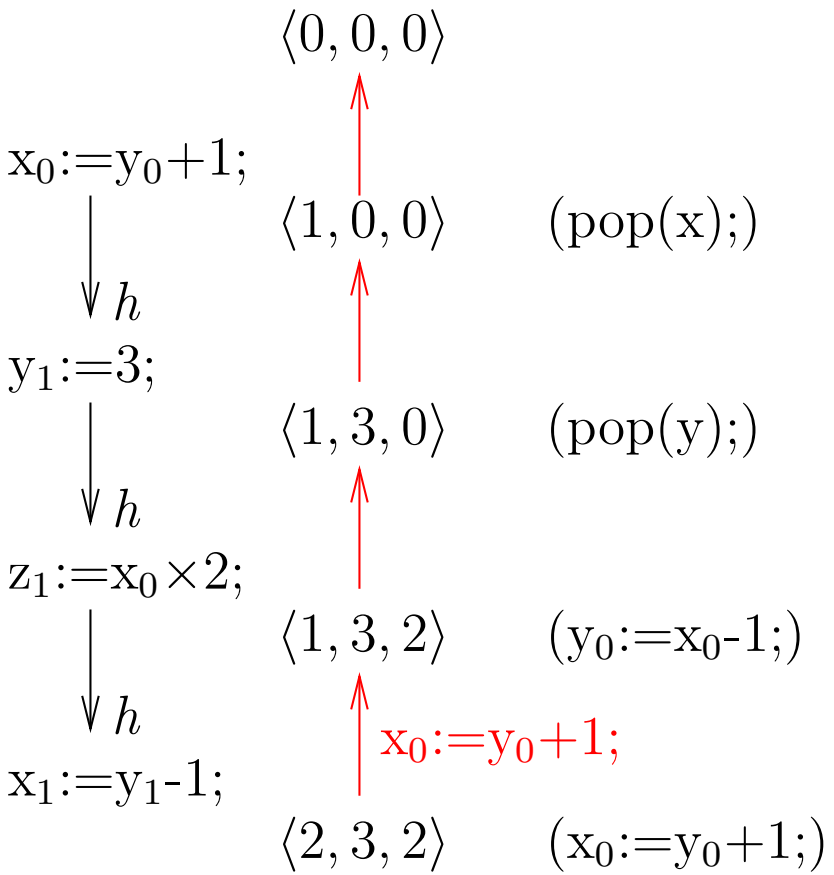

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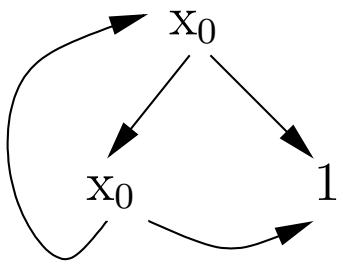
Program Validation by Symbolic Execution

$$
\begin{array}{lll}
 & \langle 0,0,0\rangle & \\
 & \uparrow & \\
x_0{:=}y_0{+}1; & \langle 1,0,0\rangle & (\mathrm{pop}(x);) \\
\downarrow h & \uparrow & \\
y_1{:=}3; & \langle 1,3,0\rangle & (\mathrm{pop}(y);) \\
\downarrow h & \uparrow & \\
z_1{:=}x_0{\times}2; & \langle 1,3,2\rangle & (y_0{:=}x_0{-}1;) \\
\downarrow h & \uparrow & \\
 & x_0{:=}(x_0{-}1){+}1; & \\
x_1{:=}y_1{-}1; & \langle 2,3,2\rangle & (x_0{:=}y_0{+}1;)
\end{array}
$$



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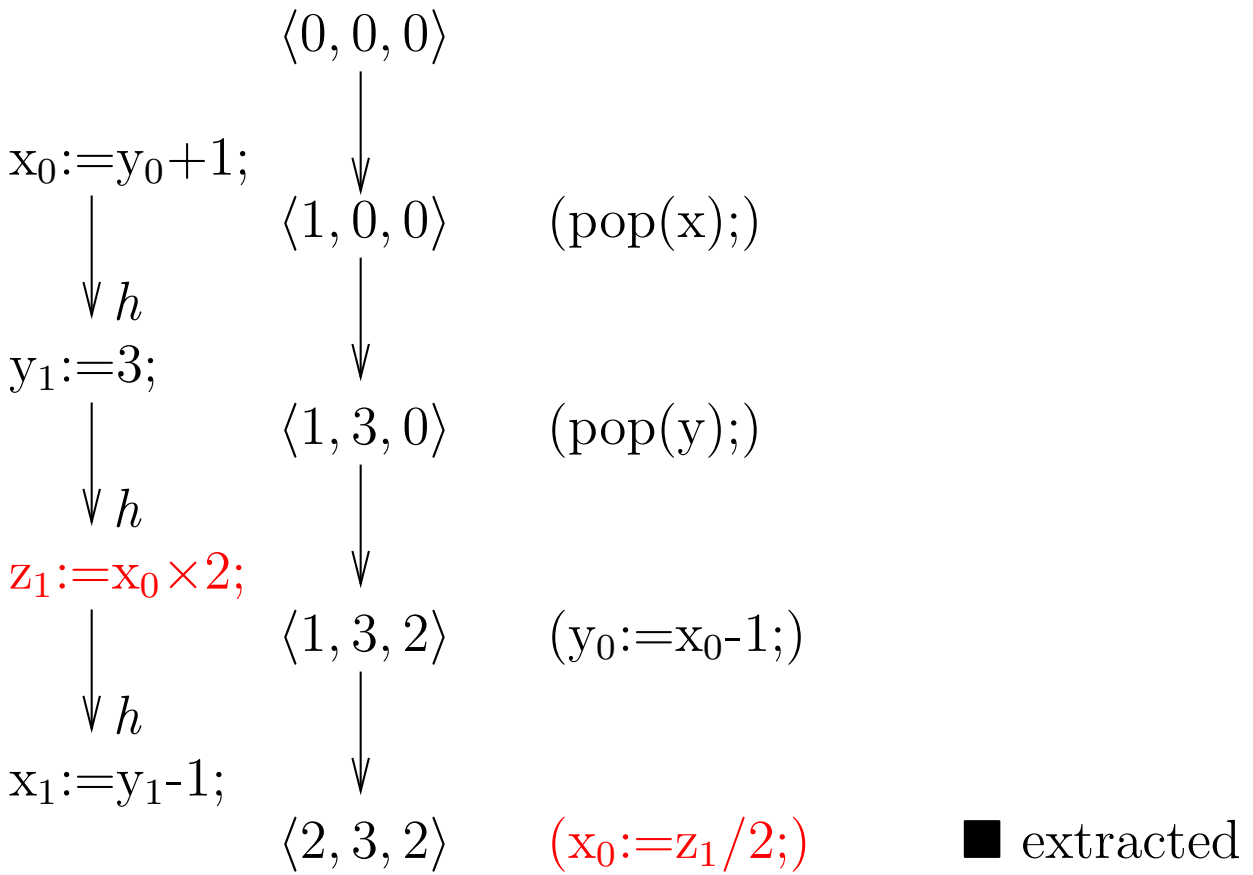

Soundness

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Program Validation by Symbolic Execution

The value of v restored by dynamic reverse code generation is the same as the previous value of v.

Proof. Suppose that the reverse code for v is $v := f(u_1, u_2, \ldots, u_n)$

1. The value of u_k either is immediately available or can be restored.
2. A reverse code is deterministically calculated.
3. The restoration of u_k does not involve v.

□

- A deterministic algorithm exploiting extraction-from-use was shown in [Lee, V&D'06].
- Conjecture: also true when redefinition/combination is used.

Bounded Buffer Example (Chapter 8)

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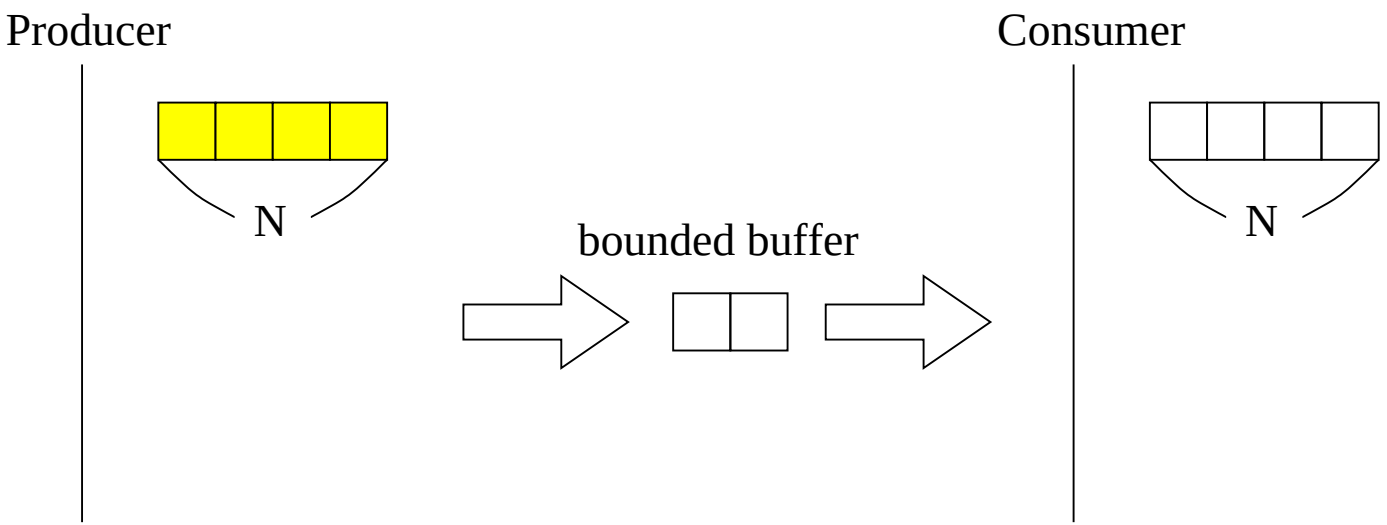
Program Validation by Symbolic Execution

- It is widely used.



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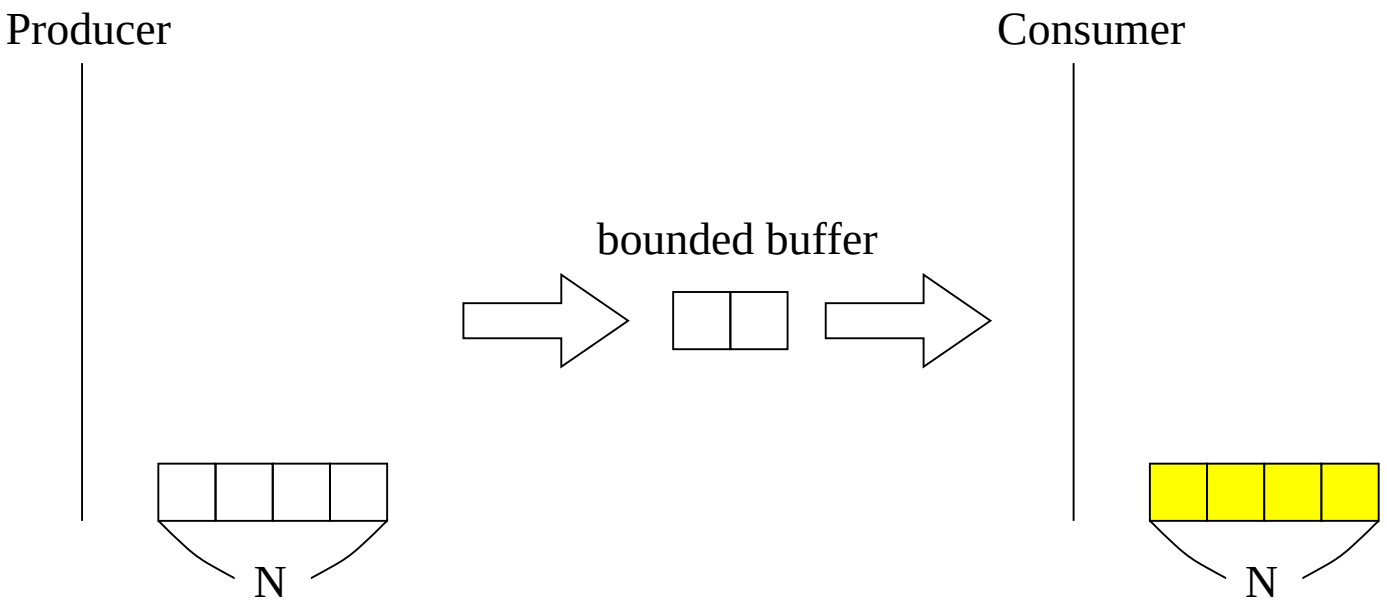

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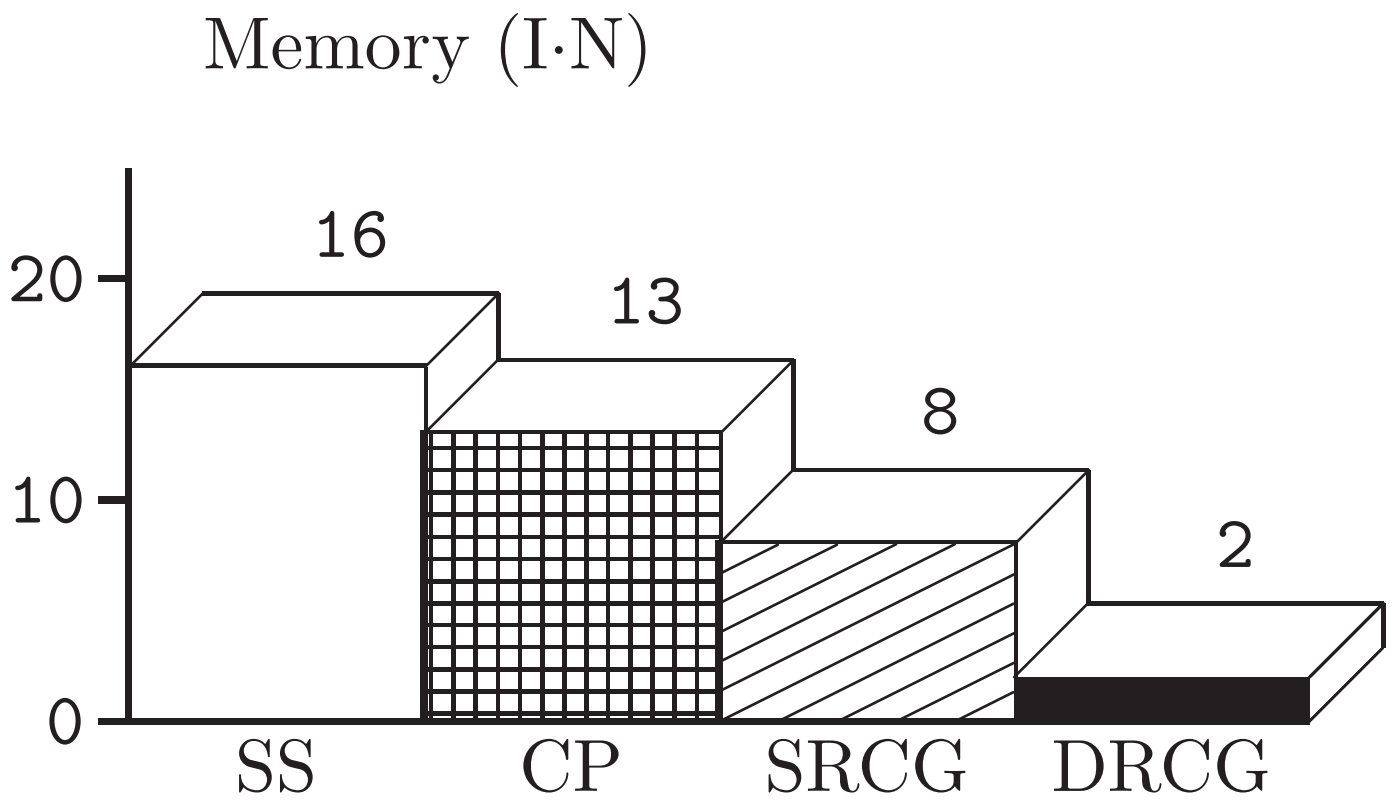

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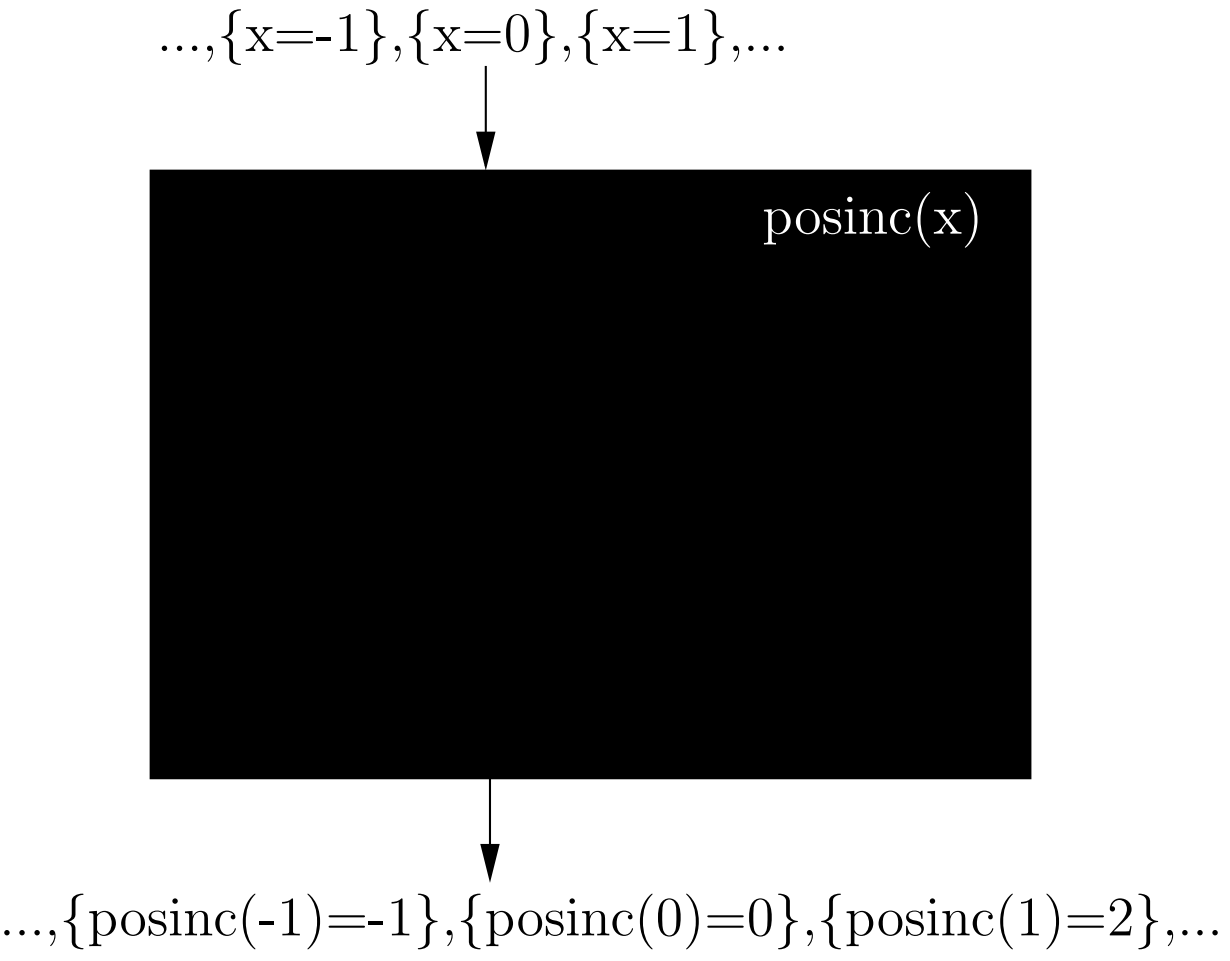

- How many input/output pairs?

Symbolic Execution

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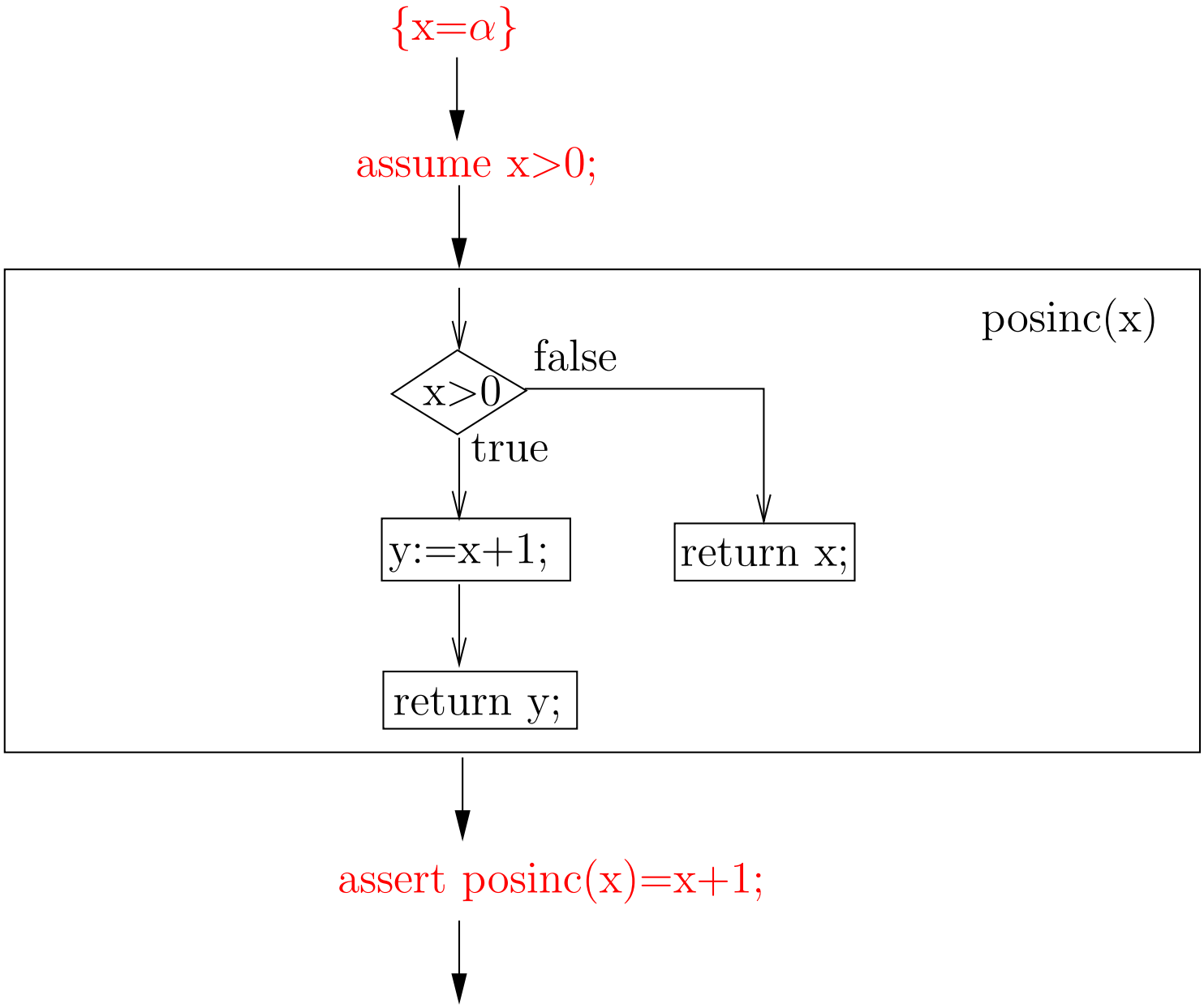

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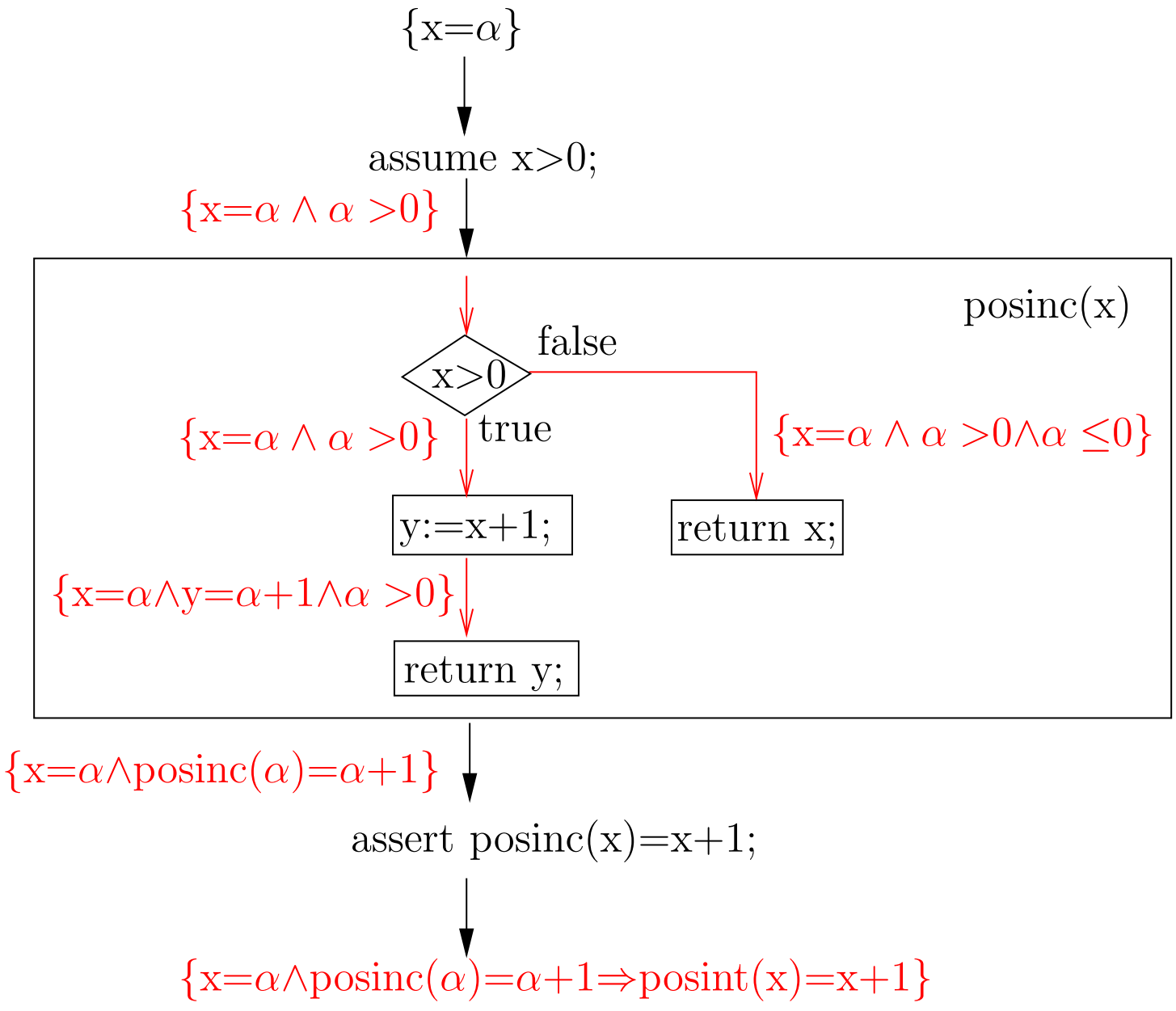

Heap

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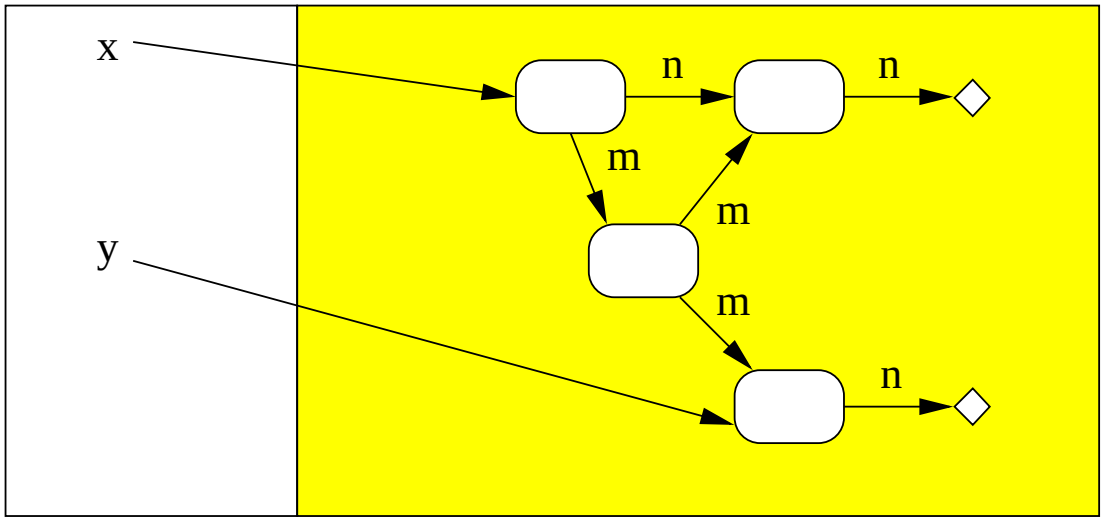

Symbolic Execution on Heap

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Concluding Remarks

$$\{x = \alpha \wedge \alpha \mapsto [f : \beta]\}$$
$$y := x.f;$$
$$\{x = \alpha \wedge y = \beta \wedge \alpha \mapsto [f : \beta]\}$$

$$\{x = \alpha \wedge y = \beta \wedge \beta \mapsto [f : -]\}$$
$$y.f := x;$$
$$\{x = \alpha \wedge y = \beta \wedge \beta \mapsto [f : \alpha]\}$$

Constraint Solver

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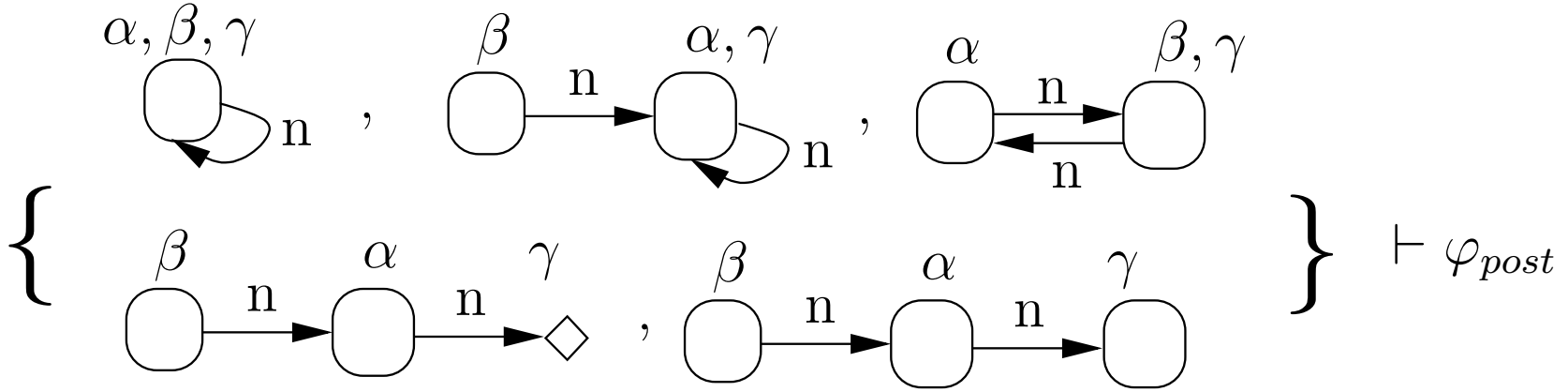
$\{\mathsf{c} = \alpha \wedge \mathsf{t} = \beta \wedge \mathsf{s} = \gamma \wedge \alpha \mapsto [\mathsf{n} : \gamma] \wedge \beta \mapsto [\mathsf{n} : \alpha]\}$
assert φ_{post};
$\{\mathsf{c} = \alpha \wedge \mathsf{t} = \beta \wedge \mathsf{s} = \gamma \wedge \alpha \mapsto [\mathsf{n} : \gamma] \wedge \beta \mapsto [\mathsf{n} : \alpha] \Rightarrow \varphi_{post}\}$



Lazy Initialization

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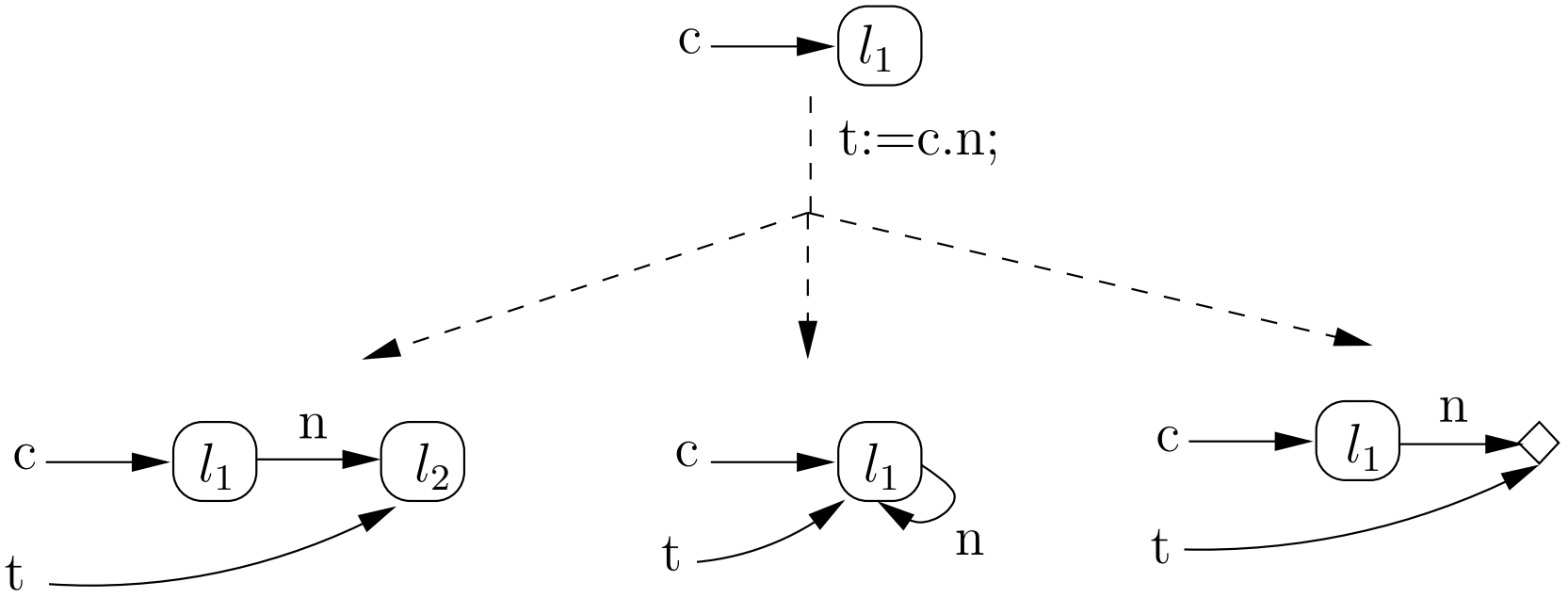
Concluding Remarks

- introduced in [Khurshid, Păsăreanu and Visser, TACAS'03]



$$type(l_1) \leq type(\mathsf{n})$$

Lazy Initialization

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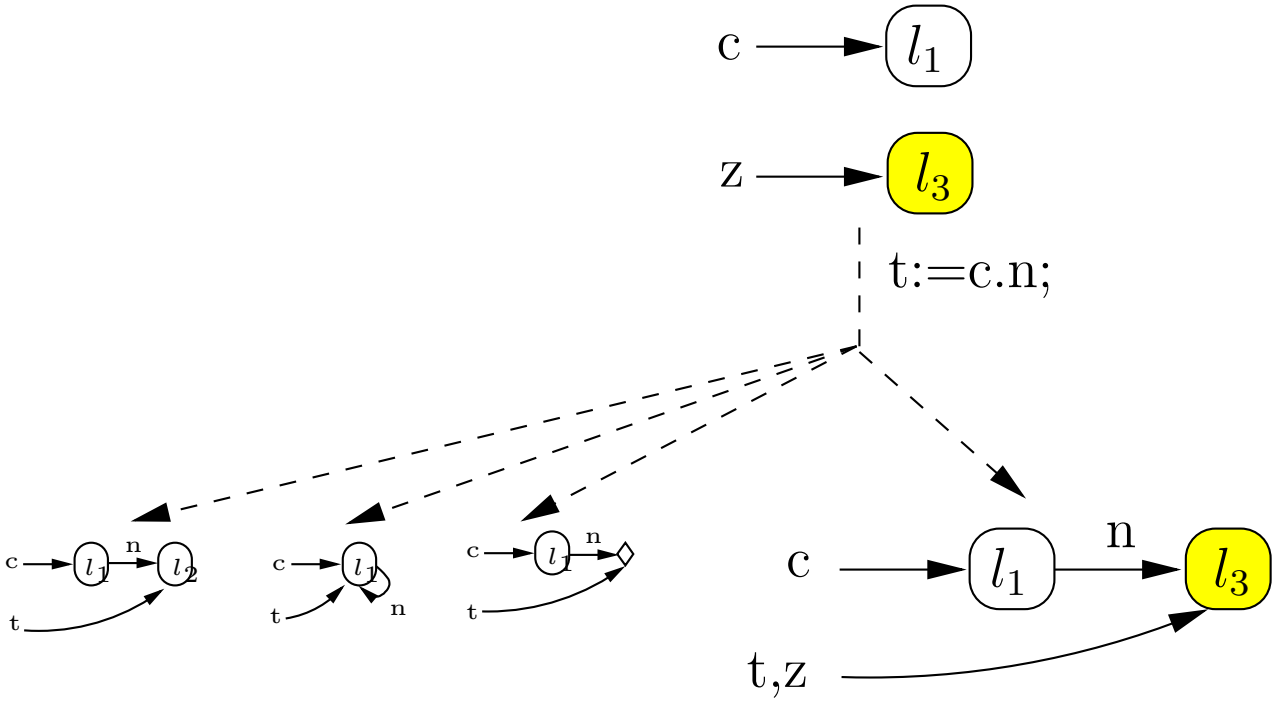

$$type(l_3) \leq type(\mathsf{n})$$

$$age(l_3) \geq age(l_1)$$

Lazier Initialization [Deng, Lee and Robby, ASE'06]

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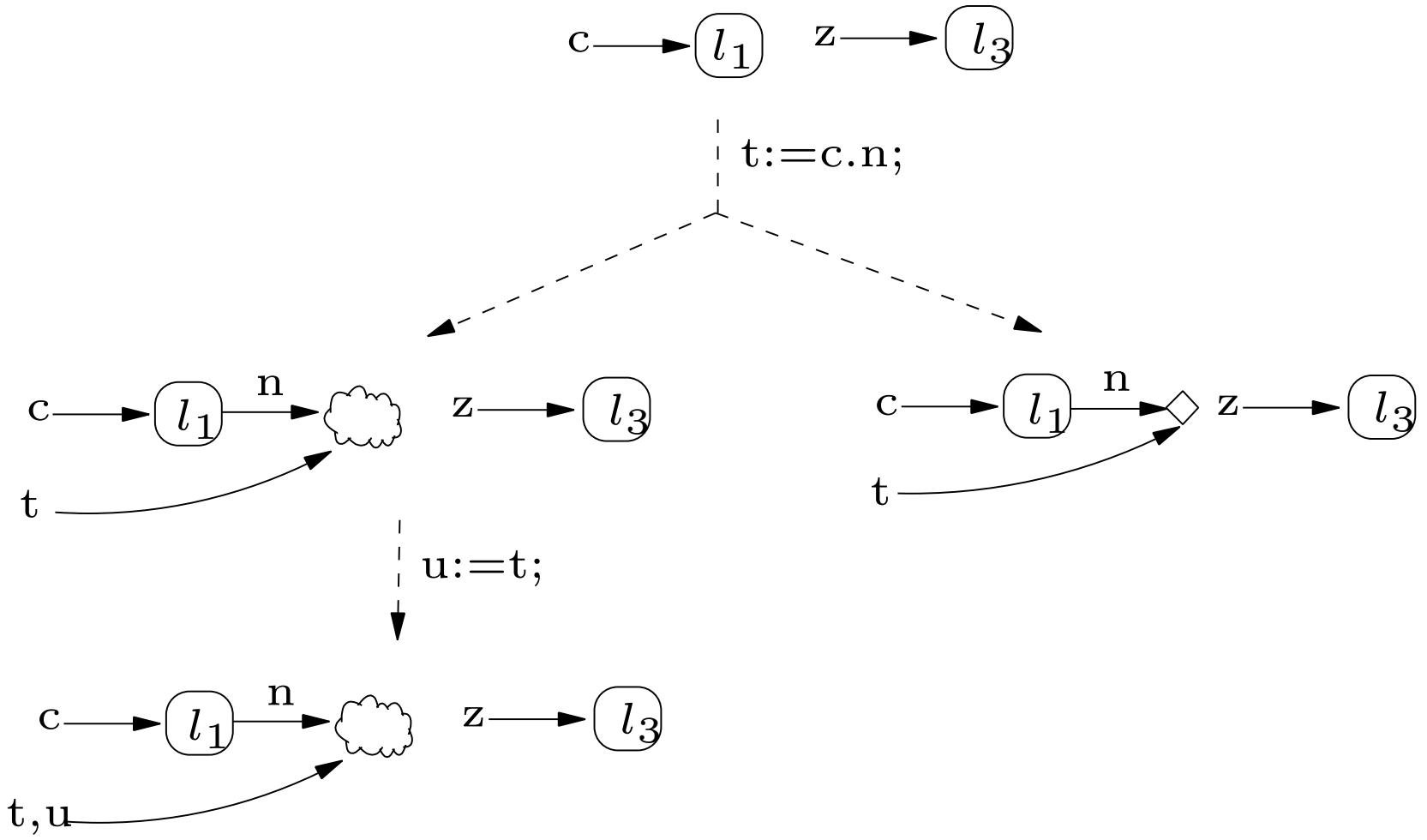

Lazier Initialization [Deng, Lee and Robby, ASE'06]

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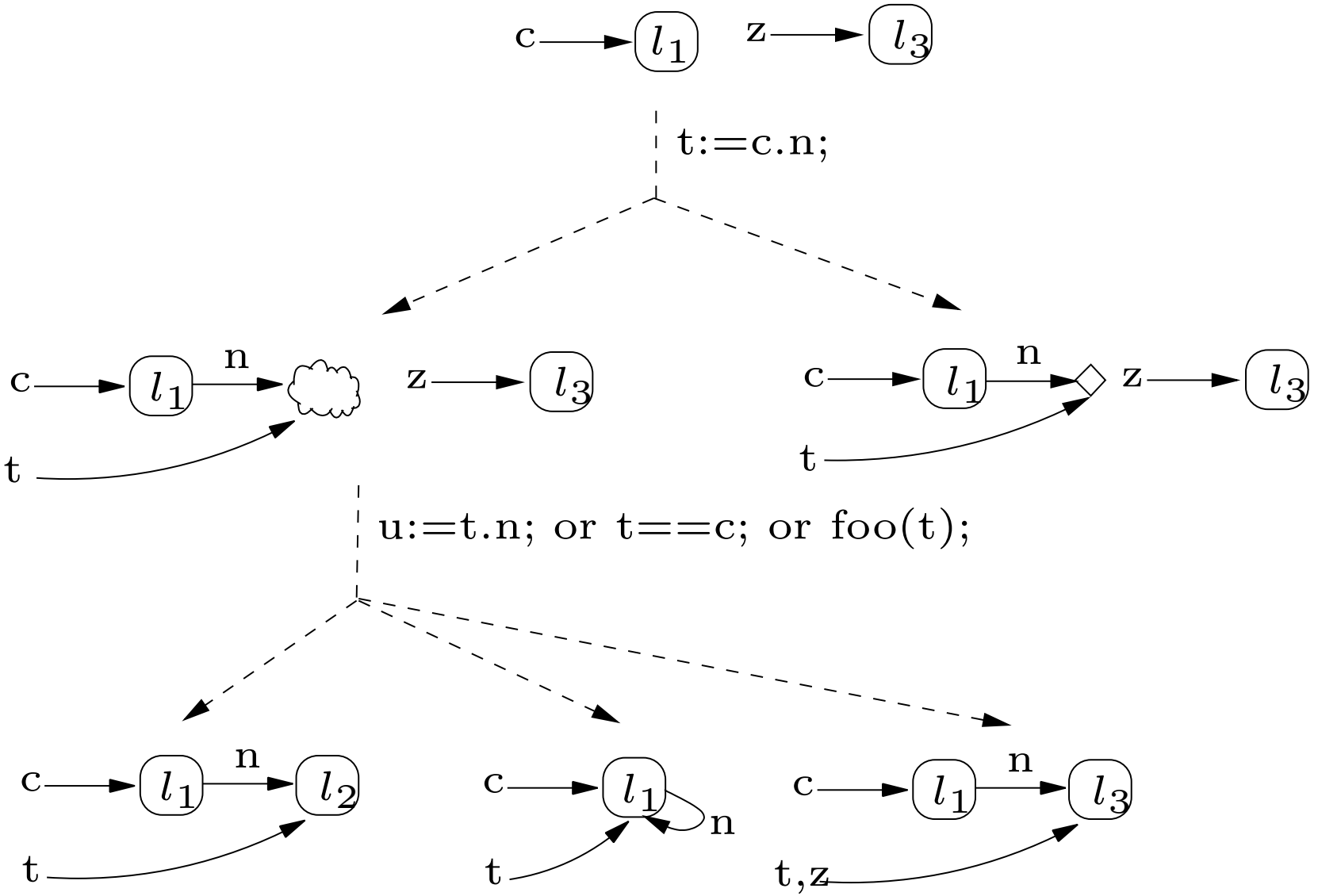

Lazy vs. Lazier

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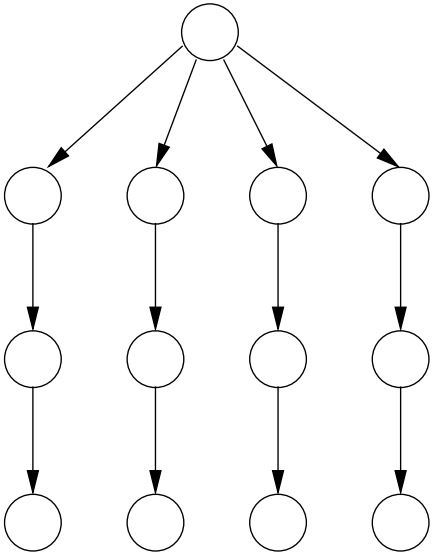
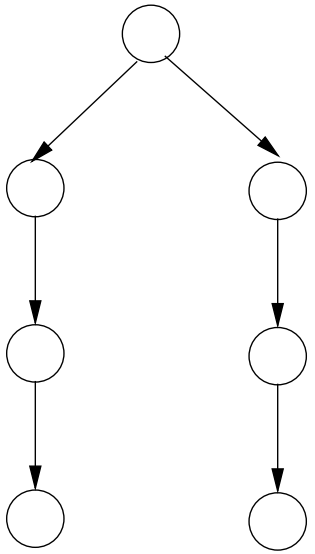
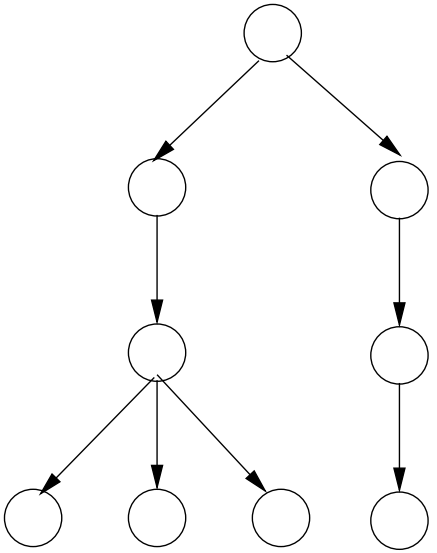


Lazier Initialization





Loop Example

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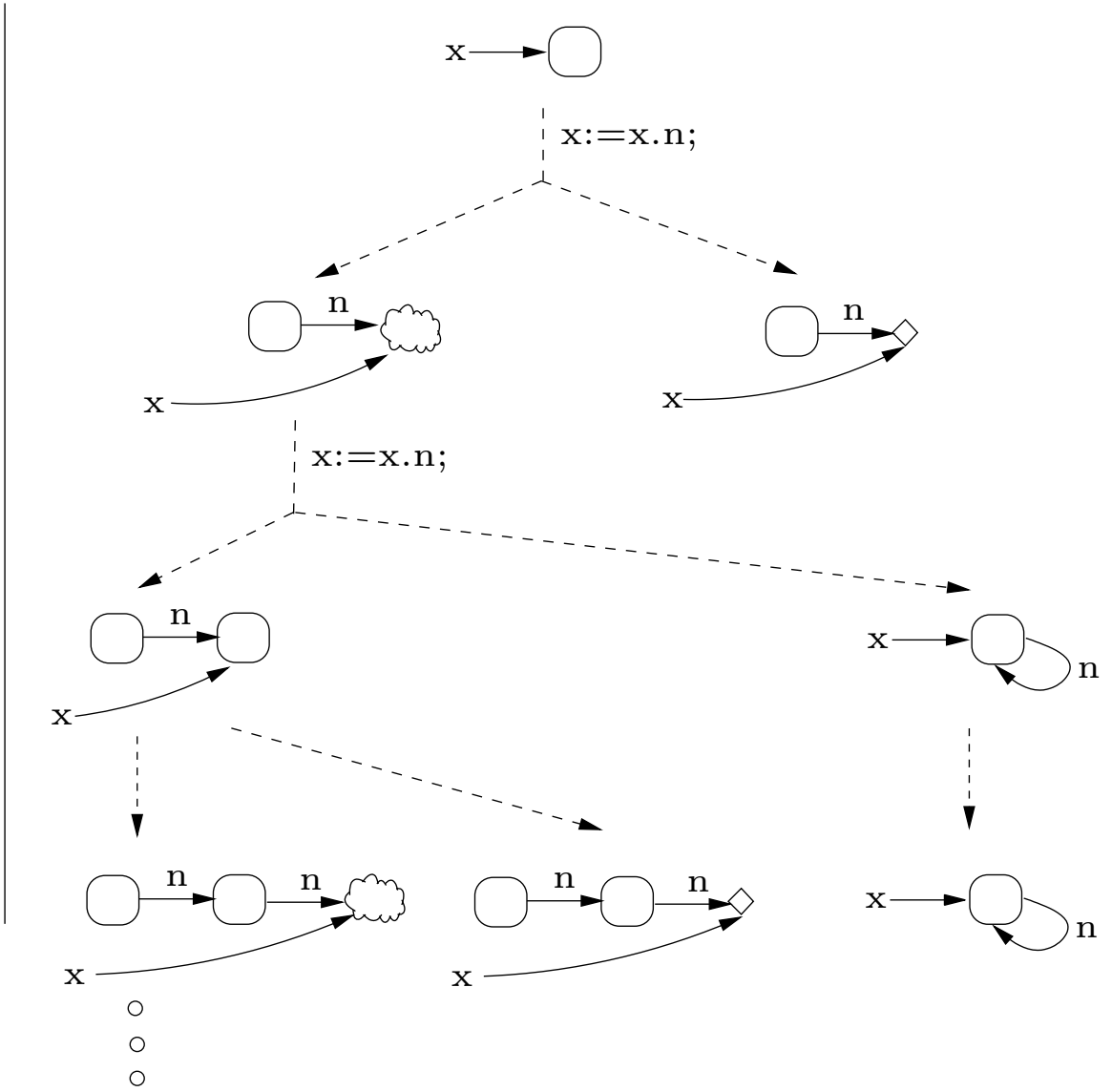
Concluding Remarks


```
bag.add(x);
while (x≠nil) {
  x:=x.n;
  if (x≠nil) {
    if(bag.has(x))
      break;
    else
      bag.add(x);
  }
}
```



Solutions

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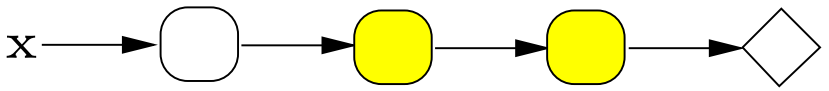
Concluding Remarks

- Loop-invariant: heavy annotation
- Abstract interpretation:
  - automatic verification
  - false alarm, scalability issue
- Bounding:
  - no false alarm
  - suitable at the early phase of validation
  - easily applicable to any program with a small bound
  - BMC (transition), Alloy (domain of variables)



$(k=2)$

initial object fresh objects

Bounded Symbolic Execution

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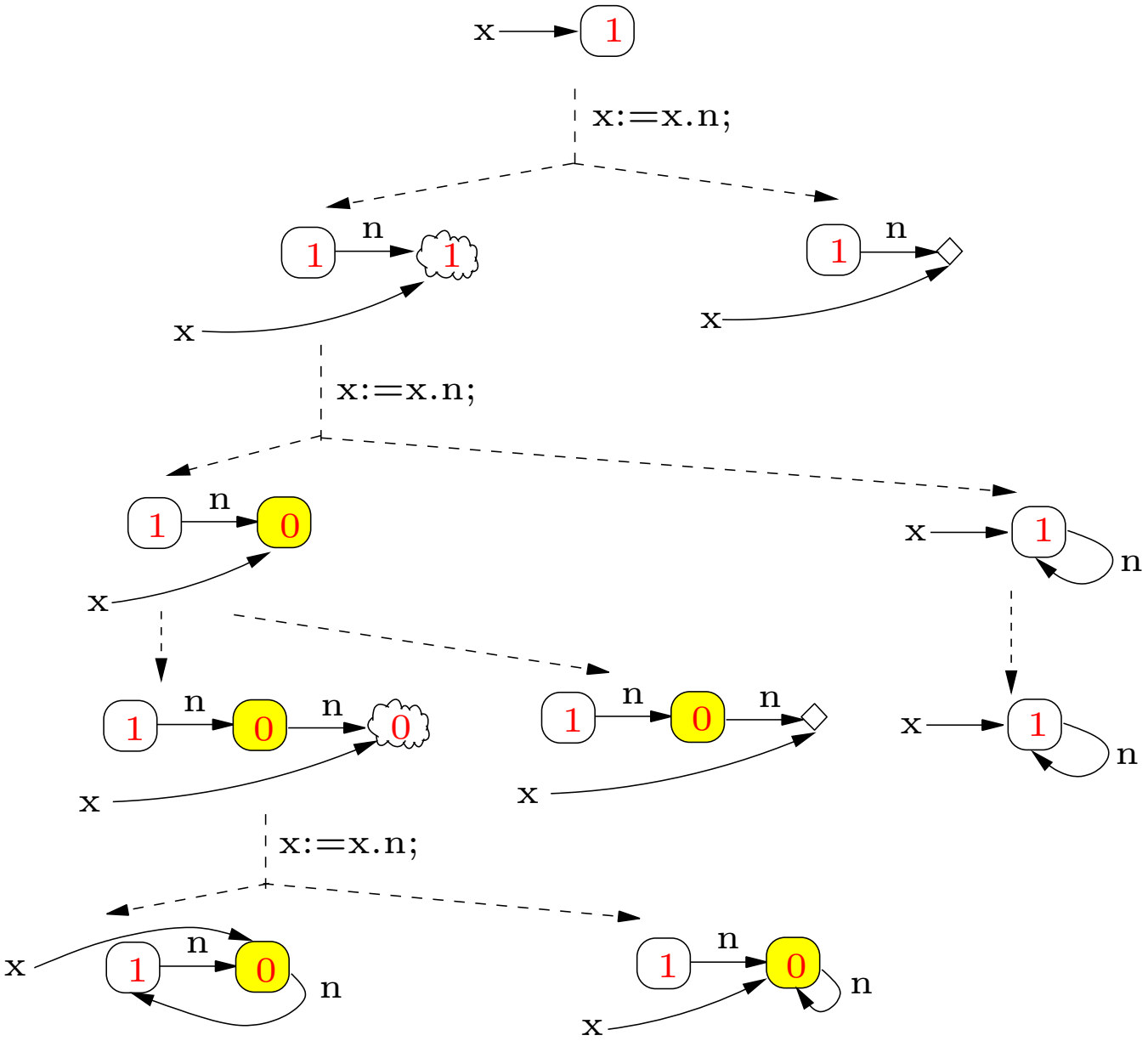

Soundness

Introduction

Reverse Execution

Program Validation by Symbolic Execution

- Testing
- Symbolic Execution
- Heap
- Symbolic Execution on Heap
- Constraint Solver
- Lazy Initialization
- Lazier Initialization
- Lazy vs. Lazier
- Loop Example
- Solutions
- Bounded Symbolic Execution
- Soundness
- Completeness
- Insertion Procedure of AVL Tree

Concluding Remarks

If an error is found by our symbolic execution, this error can take place in a concrete execution.

- Assumptions
  1. The underlying theorem prover can tell all the infeasible path conditions.
  2. Specifications of methods are reliable.
- Proof: by a simulation

Completeness

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Concluding Remarks

If an error can take place in a concrete execution, this error must be able to be found by our symbolic execution.

- Assumptions
  1. The length of every possible execution path is finite.
  2. A bound in use is sufficiently large.
  3. Specifications of methods are precise enough.
- Proof: by a simulation

Insertion Procedure of AVL Tree

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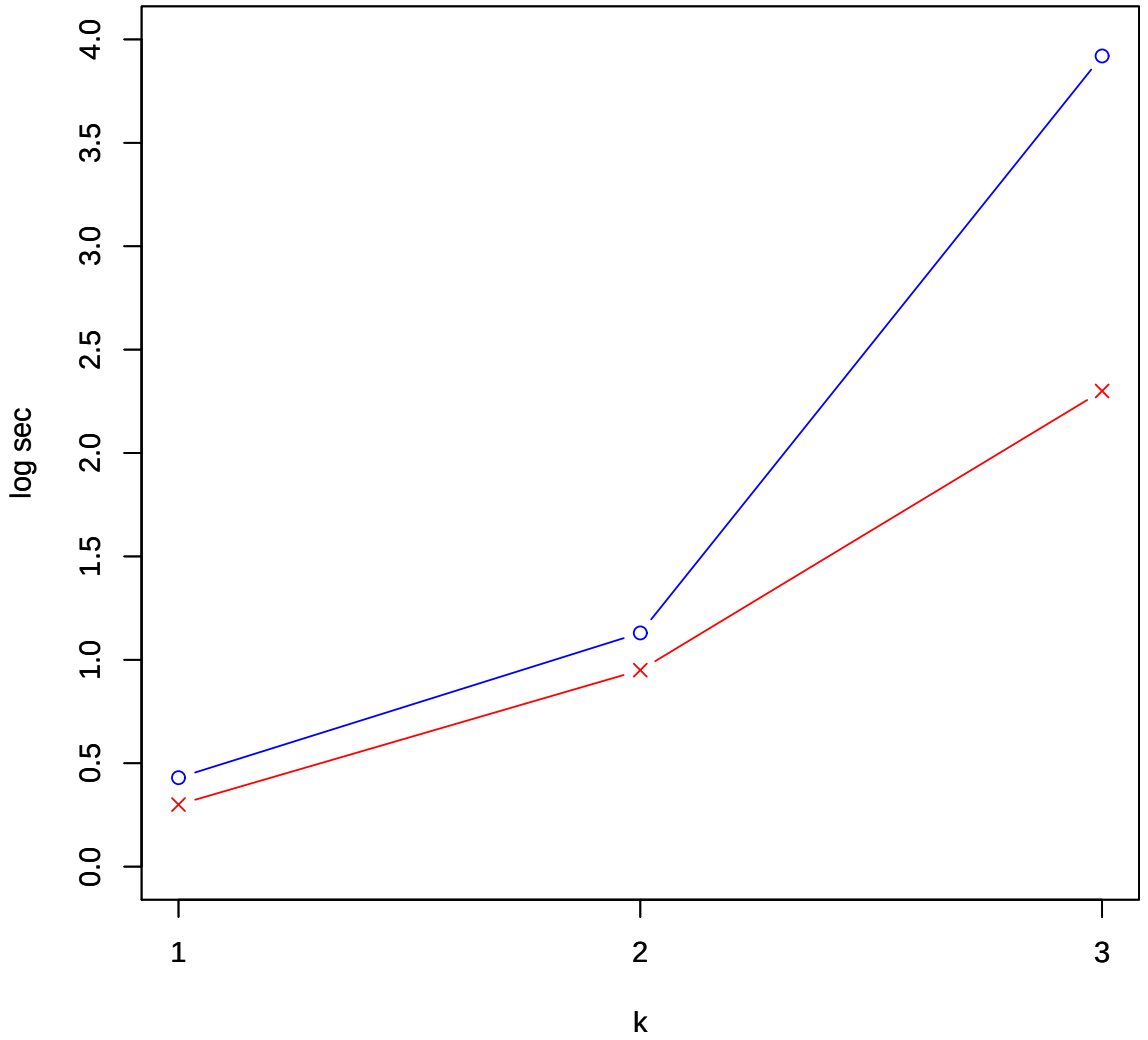
Concluding Remarks



Introduction

Reverse Execution

Program Validation by Symbolic Execution

Concluding Remarks
- Recap
- Future Work
- Publications

Concluding Remarks

Recap

Introduction
Reverse Execution
Program Validation by Symbolic Execution
Concluding Remarks
● Recap
● Future Work
● Publications

- Introduction
  - Thesis topic (what): program validation
  - Thesis topic (how): symbolic and reverse execution
- Reverse Execution
  - Reverse execution helps to locate a bug
  - Introduced dynamic reverse code generation (DRCG)
  - DRCG scales to multi-threaded programs
  - DRCG is sound
- Symbolic Execution
  - Symbolic execution helps to check for a bug
  - Introduced bounded lazier initialization (BLI)
  - BLI is useful for finding heap-related bugs
  - BLI is sound in the sense of bug-finding

Future Work

- Reverse Execution
  - Empirical studies focusing on efficient data structures and algorithms
  - Application to other languages of different paradigms
  - Exploration of a programming language suitable for reverse-code generation
- Symbolic Execution
  - Maximum bound inference
  - Loop-invariant inference

Publications

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Program Validation by Symbolic Execution

Concluding Remarks

- Recap
- Future Work
- Publications

- Jooyong Lee.
  Reverse code generation for Java program model checking.
  In *Proceedings of Winter School on Modeling and Verifying Parallel Processes (MOVEP'04)*, pages 89-95, 2004.
- Jooyong Lee.
  Dynamic reverse code generation for backward execution.
  In *Proceedings of the Post-CAV Workshop on Verification and Debugging (V&D'06)*, pages 25-43, 2006.
- Jooyong Lee.
  A case for dynamic reverse-code generation.
  Submitted.
- Xianghua Deng, Jooyong Lee and Robby.
  Bogor/Kiasan: A k-bounded Symbolic Execution for Checking Strong Heap Properties of Open Systems.
  In *Proceedings of Conference on Automated Software Engineering (ASE'06)*, pages 157-166, 2006.