Stateless Model Checking Concurrent/Distributed Programs

Michalis Kokologiannakis   Viktor Vafeiadis

POPL 2025

Why concurrency?

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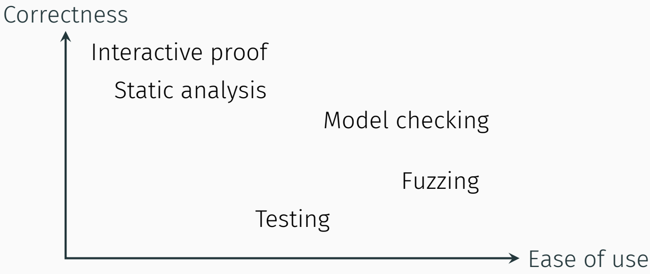

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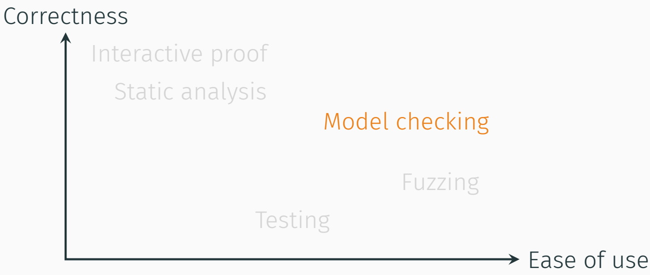

Model-checking approaches

Stateful:

- Visit program states while recording visited states
- Assumes program has bounded state-space
- High memory usage

Stateless:

- Visit program states without recording visited states
- Assumes program always terminates
- Low memory usage

SMT-based:

- Encode program and specification as an SMT query
- Assumes program always terminates
- High memory usage

Our weapon of choice

[PLDI'19] Model checking weakly-consistent libraries

[POPL'22] Truly stateless, optimal dynamic partial order reduction

GenMC: state-of-the-art stateless model checker

- Correct, optimal, highly-parallelizable
- Works with almost any memory model
- Small memory footprint

plv.mpi-sws.org/genmc

Two papers in POPL'25 (Thu @ 15:00):

- Automatically checking linearizability under weak memory consistency
- Model checking C/C++ with mixed-size accesses

Outline

How does GenMC work?

- SMC basics
- Execution graphs
- Exploration algorithm

How to apply GenMC to our code?

- State-space reductions
- Estimating state-space size
- Exploration bounding

Each part will be followed by a demo

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$$x := 1 \;\Big\|\; y := 1 \;\Big\|\; a := x$$

a = 1

$x := 1$	$y := 1$	$x := 1$
↓	↓	↓
$y := 1$	$x := 1$	$a := x$
↓	↓	↓
$a := x$	$a := x$	$y := 1$

a = 0

$a := x$	$a := x$	$y := 1$
↓	↓	↓
$x := 1$	$y := 1$	$a := x$
↓	↓	↓
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↓	↓	↓
$a := x$	$a := x$	$y := 1$

$a = 0$

$a := x$	$a := x$	$y := 1$
↓	↓	↓
$x := 1$	$y := 1$	$a := x$
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$y := 1$	$x := 1$	$x := 1$

How to enumerate one interleaving per equivalence class?

(Partial order reduction)

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Interlude: Semantics under weak memory consistency

Interlude: Declarative semantics under WMC

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$$[\![P]\!]_M \triangleq \left\{ \mathsf{G} \in \mathrm{ExecGraphs}(P) \;\middle|\; \mathrm{cons}_M(G) \right\}$$

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$$[data = flag = 0]$$

$$
\begin{array}{l|l}
data := 42 & \mathtt{if}\ (flag = 1) \\
flag := 1 & \quad \mathtt{assert}(data = 42)
\end{array}
$$

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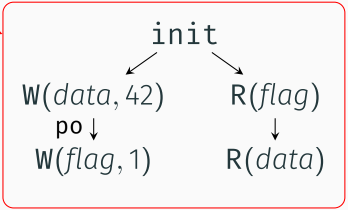

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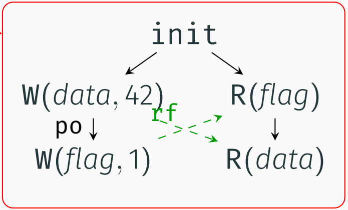

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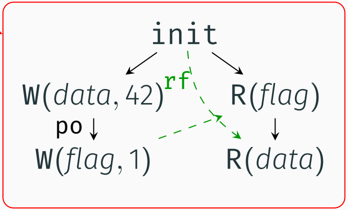

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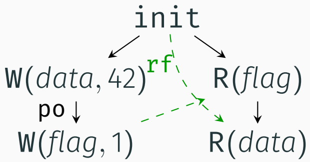

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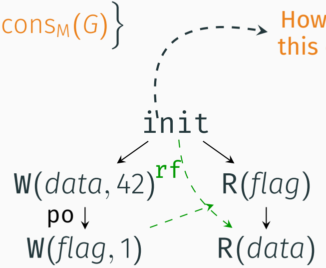
How to forbid this outcome?



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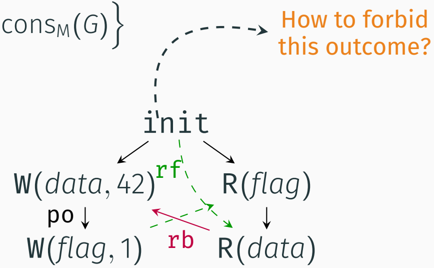

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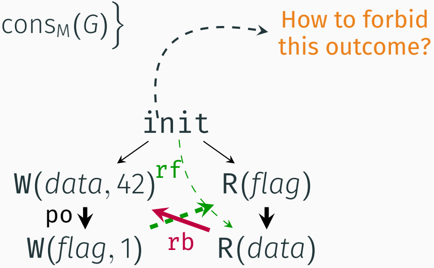

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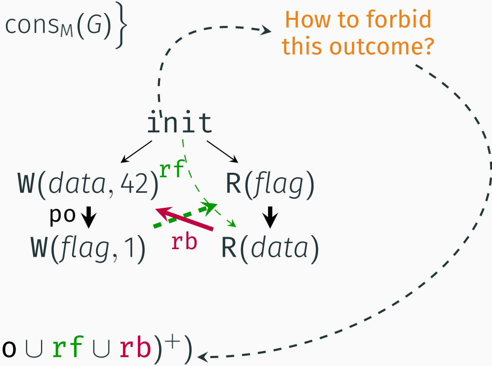

Fictional model M: irreflexive$((\mathtt{po} \cup \mathtt{rf} \cup \mathtt{rb})^+)$

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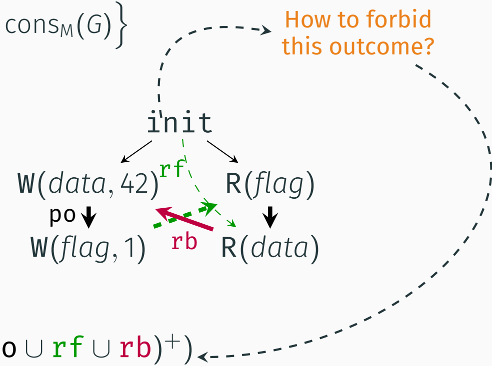

Fictional model M: $\mathrm{irreflexive}((\mathtt{po} \cup \mathtt{rf} \cup \mathtt{rb})^+)$

Real model SC: $\mathrm{irreflexive}((\mathtt{po} \cup \mathtt{rf} \cup \mathtt{co} \cup \mathtt{rb})^+)$

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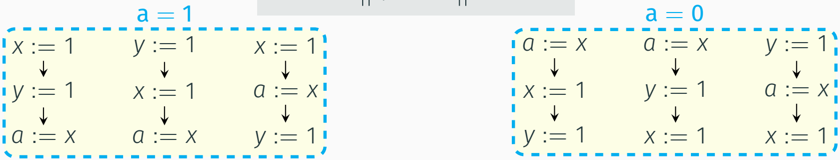

Key Idea: Represent equivalence classes with execution graphs

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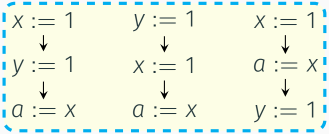

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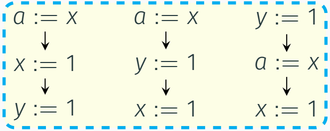
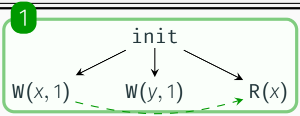
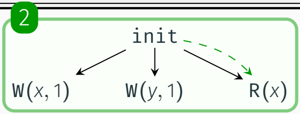


Key Idea: Represent equivalence classes with execution graphs





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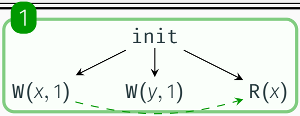

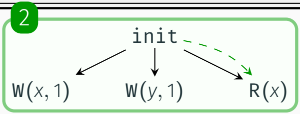

We can verify programs by enumerating consistent execution graphs!

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- $x := 1 \to y := 1 \to a := x$
- $y := 1 \to x := 1 \to a := x$
- $x := 1 \to a := x \to y := 1$

$a = 0$

- $a := x \to x := 1 \to y := 1$
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Key Idea: Represent equivalence classes with execution graphs

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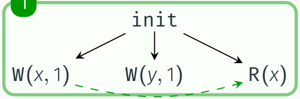

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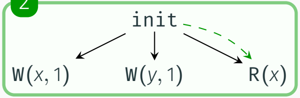

does not assume SC

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GenMC's algorithm: Example #1

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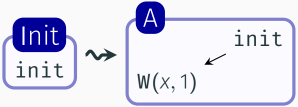

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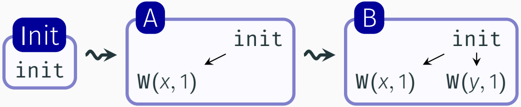

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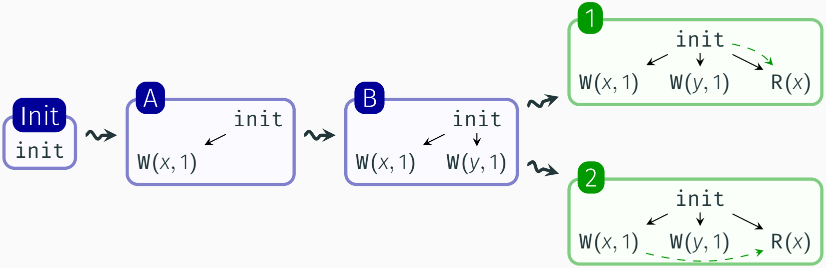

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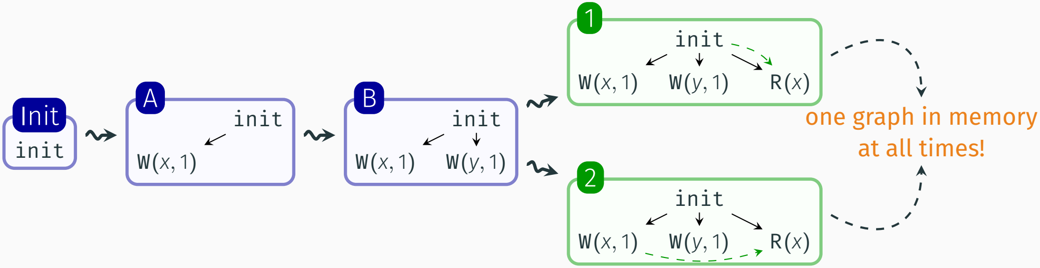

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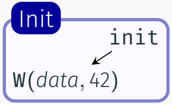

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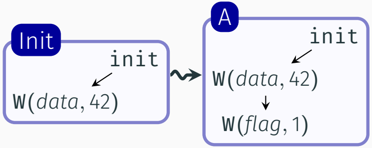

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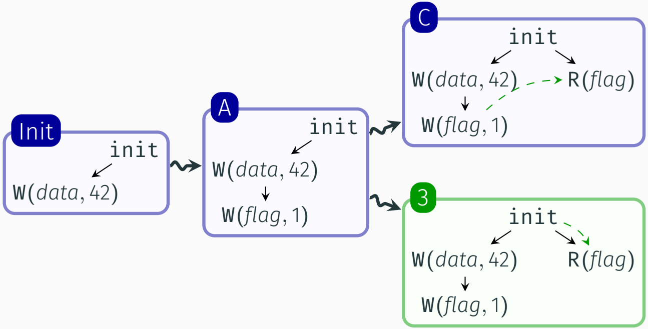

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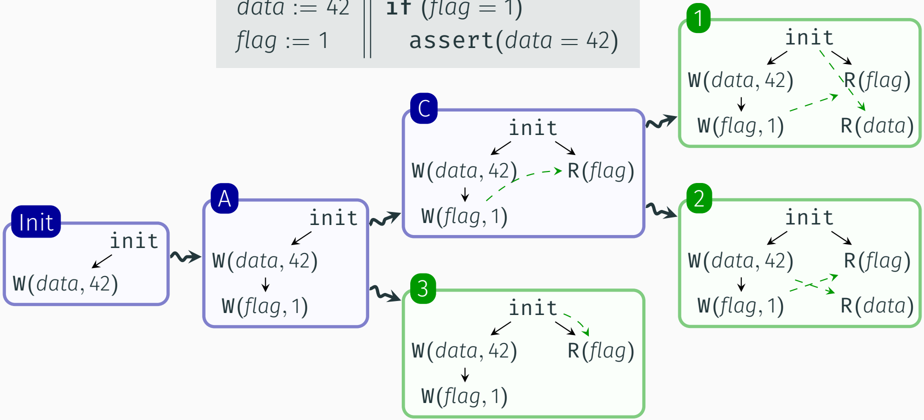

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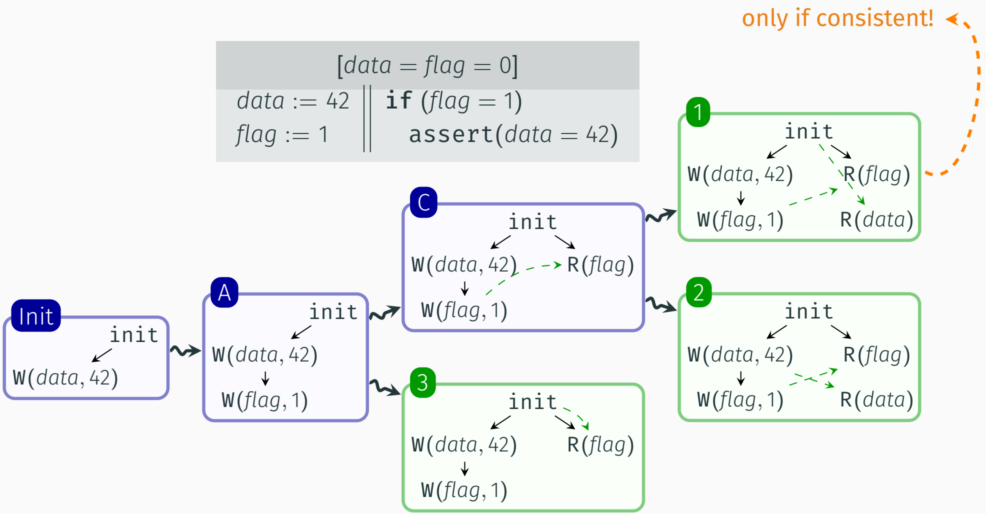

GenMC's algorithm: Example #3

$[x = y = 0]$	
$a := x$ $y := a + 1$	$x := 1$

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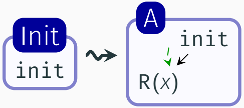
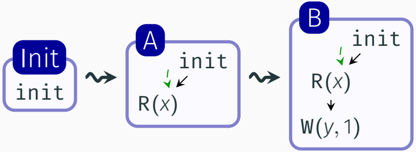


GenMC's algorithm: Example #3

$$[x = y = 0]$$

$$\begin{array}{l} a := x \\ y := a + 1 \end{array} \quad \Big\| \quad x := 1$$



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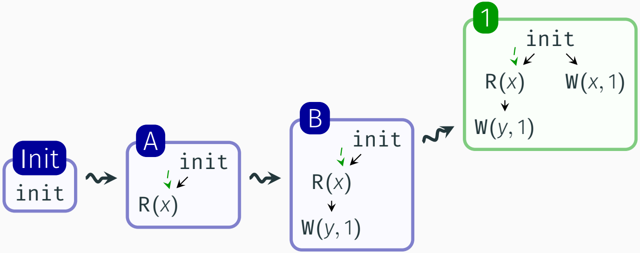
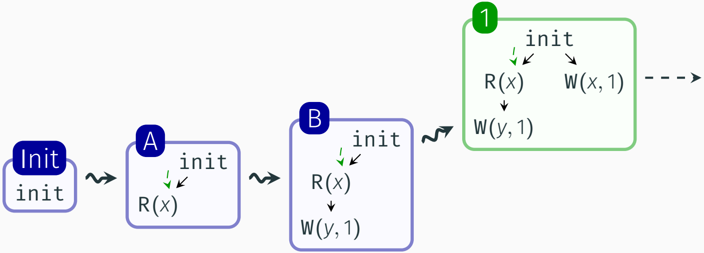
$[x = y = 0]$		
$a := x$ $y := a + 1$	$\|\|$	$x := 1$



GenMC's algorithm: Example #3

$$[x = y = 0]$$

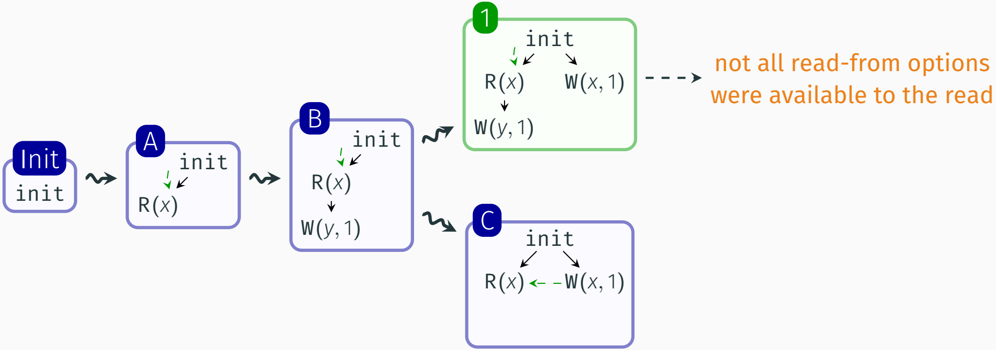
$$\begin{array}{l} a := x \\ y := a + 1 \end{array} \;\Bigg\|\; x := 1$$



not all read-from options were available to the read

GENMC's algorithm: Example #3

$[x = y = 0]$	
$a := x$ $y := a + 1$	$x := 1$



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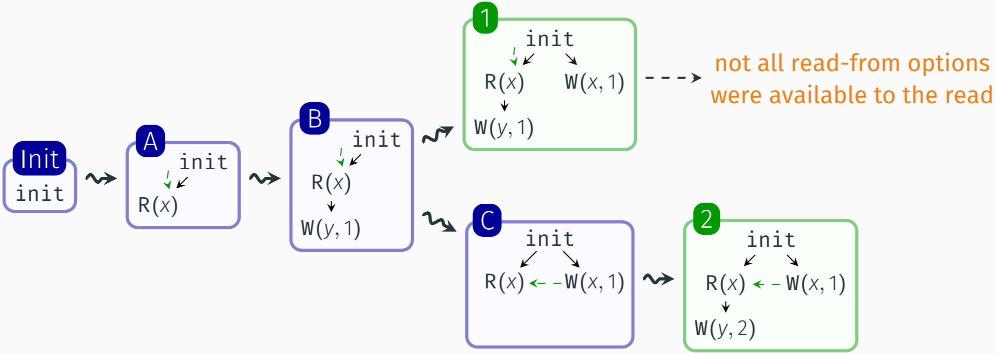

GenMC's algorithm: Example #4

$[x = y = 0]$		
$a := x$ $y := a + 1$	$b := y$	$x := 1$

GenMC's algorithm: Example #4

$$[x = y = 0]$$

$$\begin{array}{l} a := x \\ y := a + 1 \end{array} \;\Big\|\; b := y \;\Big\|\; x := 1$$

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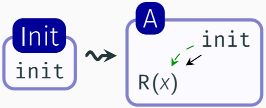

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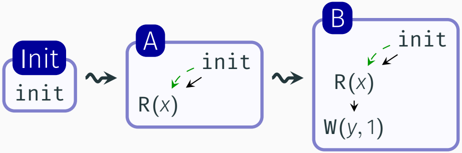
$$[x = y = 0]$$

$a := x$ $y := a + 1$	$b := y$	$x := 1$



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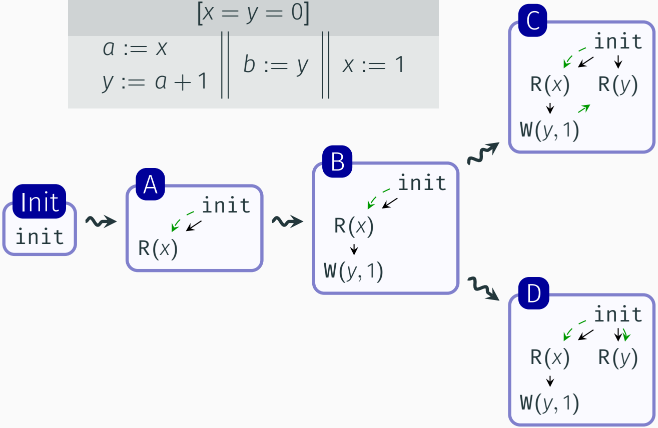

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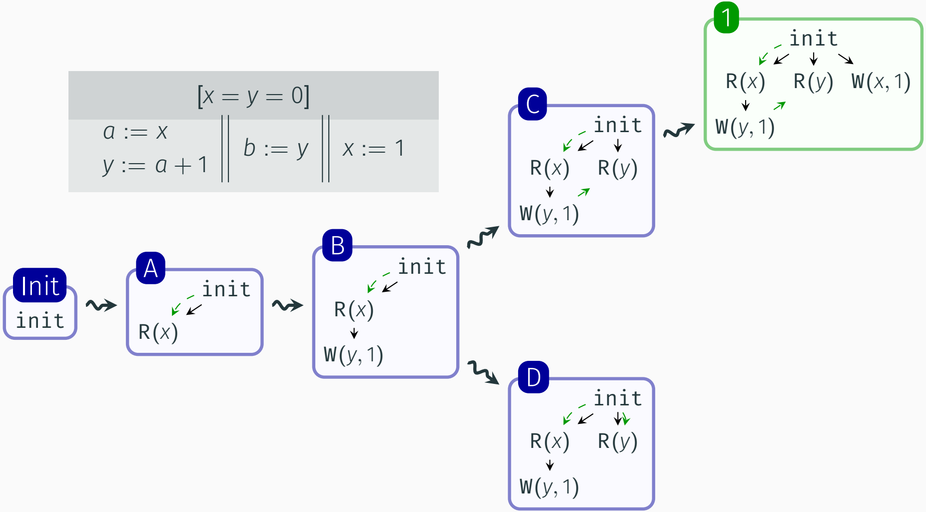

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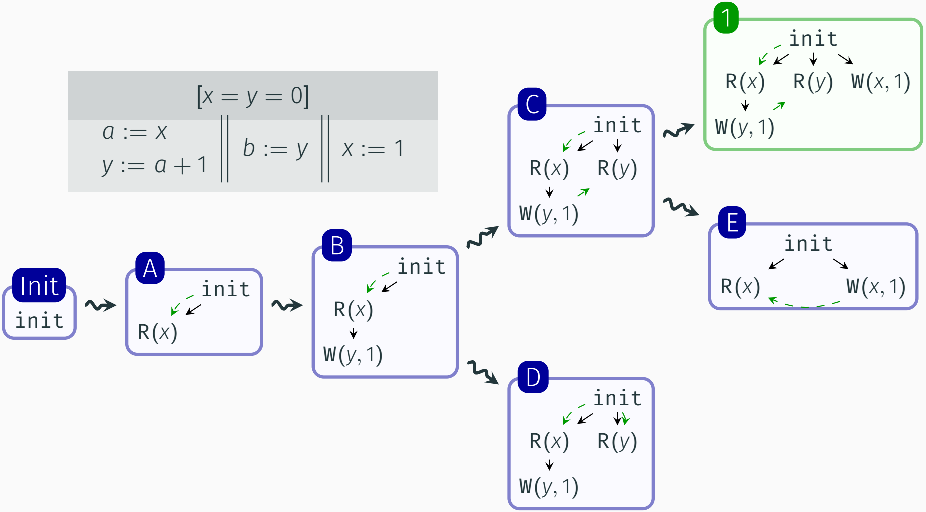

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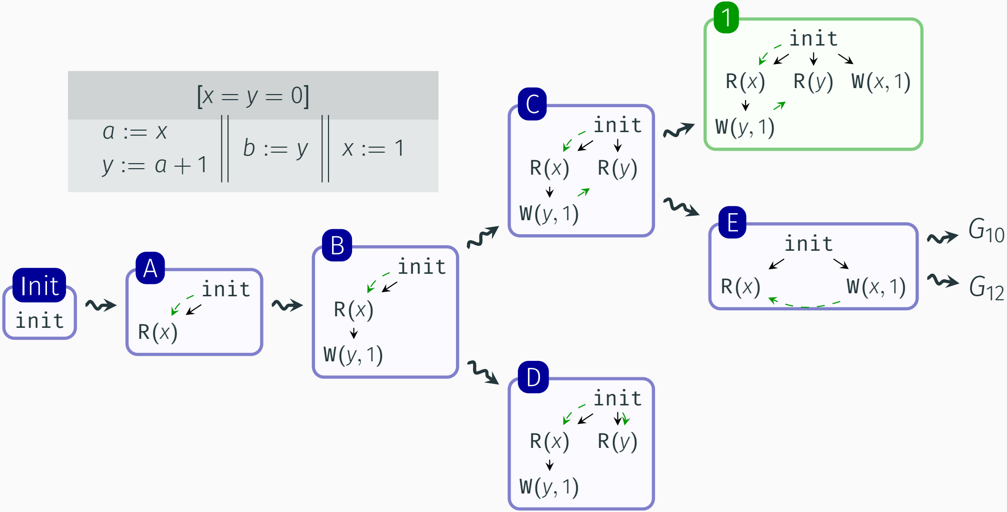

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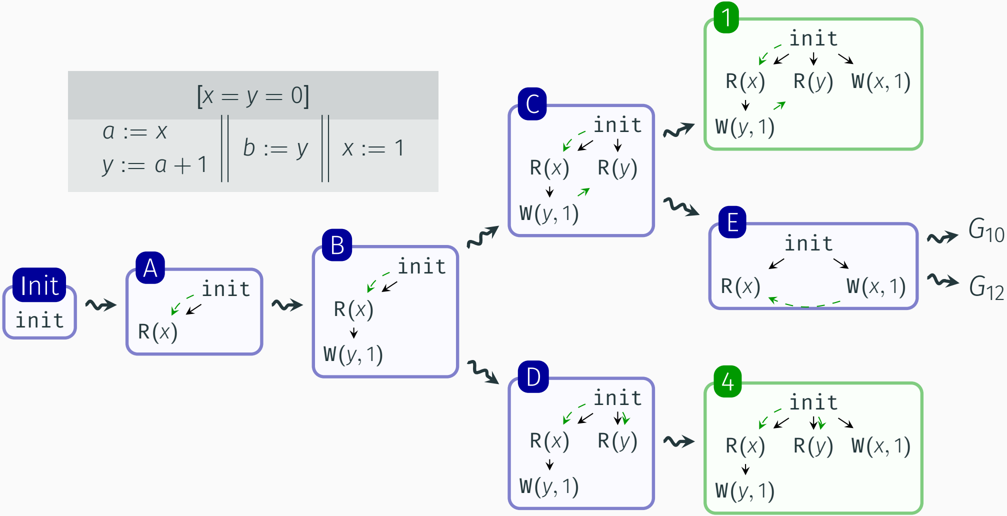

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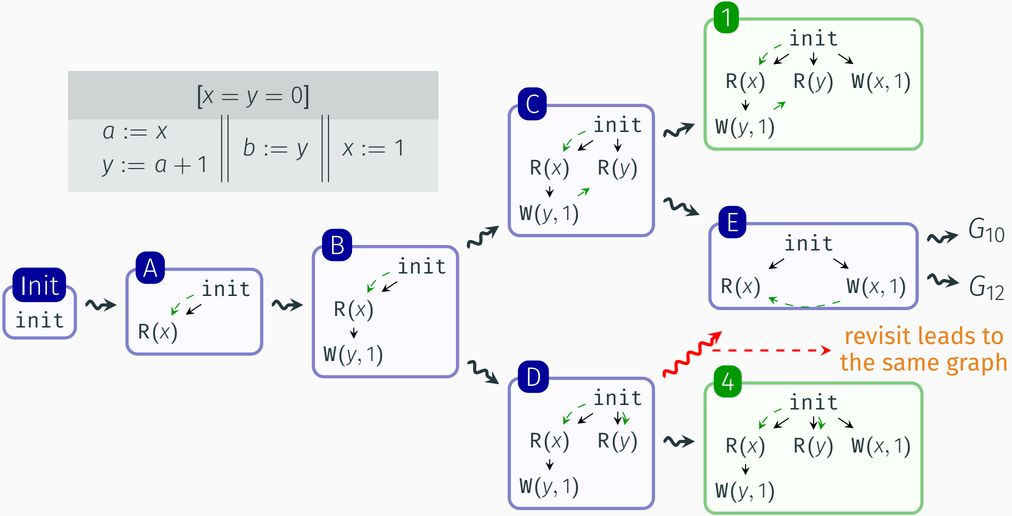

GENMC's algorithm: Example #4

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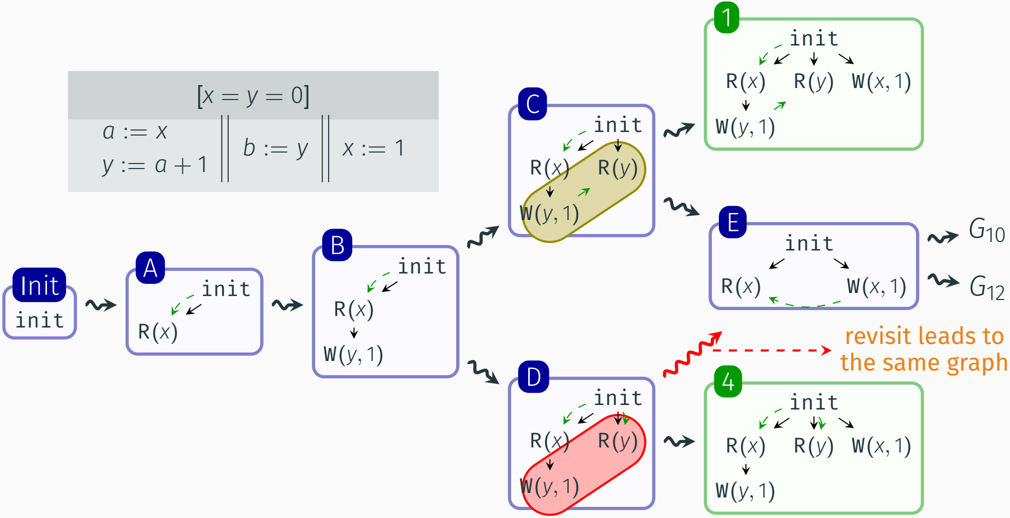

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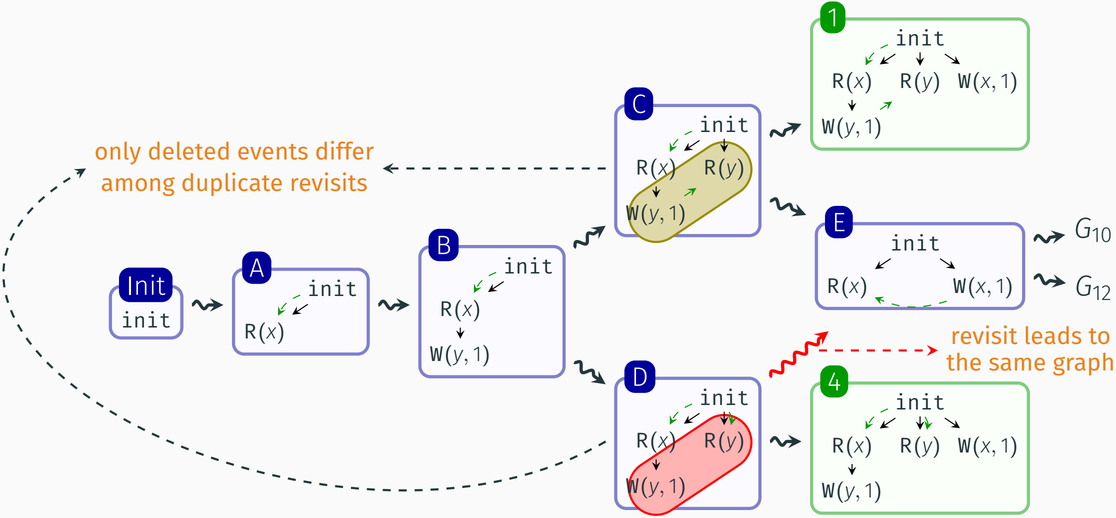

Memory-model conditions

GenMC enumerates all consistent execution graphs for **any** memory model M, if

- $\text{cons}_M(\cdot)$ implies irreflexive($(\texttt{po} \cup \texttt{rf})^+$)
- $\text{cons}_M(\cdot)$ is **prefix-closed**
- $\text{cons}_M(\cdot)$ is **maximally extensible**

Memory-model conditions

GenMC enumerates all consistent execution graphs for **any** memory model M, if

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- $\text{cons}_M(\cdot)$ is **prefix-closed**
- $\text{cons}_M(\cdot)$ is **maximally extensible**

These conditions hold for SC, TSO, PSO, RC11
(can be relaxed for POWER, ARM, IMM, LKMM)

Outline

How does GenMC work?

- SMC basics
- Execution graphs
- Exploration algorithm

How to apply GenMC to our code?

- State-space reductions
- Estimating state-space size
- Exploration bounding

Each part will be followed by a demo

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Demo #1

1. **Install Docker:**

   Debian/Ubuntu:
   ```
   apt install docker.io
   ```
   MacOS:
   ```
   brew install --cask docker
   ```
   Windows:
   ```
   wsl --install
   apt install docker.io
   ```

2. **Run GenMC container:**
   ```
   docker pull genmc/genmc
   docker run -it genmc/genmc:latest
   ```

3. **Download tutorial material:**
   ```
   wget https://plv.mpi-sws.org/genmc/popl2025/examples.tar.gz
   ```

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Approaches for state-space explosion

Partial order reduction (POR):

Avoid ordering independent actions

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Avoid ordering independent actions

$a_1 = \ldots = a_N = 0$
$a_1 := 1 \parallel \ldots \parallel a_N := N$

$$\#\text{ of executions} \begin{cases} \text{SMC}: N! \\ \text{POR}: \quad 1 \\ \qquad \vdots \end{cases}$$

Approaches for state-space explosion

Partial order reduction (POR):

Avoid ordering independent actions

$a_1 = \ldots = a_N = 0$
$a_1 := 1 \parallel \ldots \parallel a_N := N$

$$\text{\# of executions} \begin{cases} \text{SMC}: & N! \\ \text{POR}: & 1 \\ & \vdots \end{cases}$$

Symmetry reduction (SR):

Avoid ordering symmetric threads

Approaches for state-space explosion

Partial order reduction (POR):

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$a_1 = \ldots = a_N = 0$
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$$\#\text{ of executions} \begin{cases} \text{SMC} : N! \\ \text{POR} : \ \ 1 \\ \text{SR} \ \ \ : N! \end{cases}$$

Symmetry reduction (SR):

Avoid ordering symmetric threads

Approaches for state-space explosion

Partial order reduction (POR):

Avoid ordering **independent actions**

$a_1 = \ldots = a_N = 0$
$a_1 := 1 \parallel \ldots \parallel a_N := N$

$$\# \text{ of executions} \begin{cases} \text{SMC}: N! \\ \text{POR}: 1 \\ \text{SR}: N! \end{cases}$$

Symmetry reduction (SR):

Avoid ordering **symmetric threads**

$x = 0$
`fetch_add`$(x, 1) \parallel \ldots \parallel$ `fetch_add`$(x, 1)$

$$\# \text{ of executions} \begin{cases} \text{SMC}: N! \\ \text{POR}: N! \\ \text{SR}: 1 \end{cases}$$

Combining SR and POR

[PLDI'24] SPORE: Combining symmetry and partial order reduction

$$x = a[1] = \ldots = a[N] = 0$$

$$\begin{array}{l} i := \texttt{fetch\_add}(x, 1) \\ a[i] := i \end{array} \;\Big\|\; \ldots \;\Big\|\; \begin{array}{l} i := \texttt{fetch\_add}(x, 1) \\ a[i] := i \end{array}$$

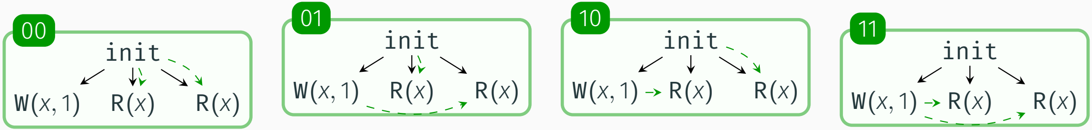
SMC	: $(2N)!/(N \cdot 2!)$
POR	: $N!$
SR	: $(2N-1)!!$
POR +SR	: 1

Combining SR and POR

[PLDI'24] SPORE: Combining symmetry and partial order reduction

$[x = 0]$

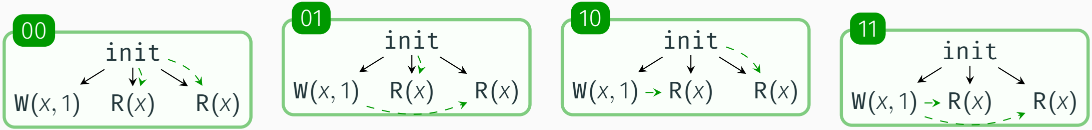
T1: $x := 1$ || T2: $r := x$ || T3: $r := x$



Combining SR and POR

[PLDI'24] SPORE: Combining symmetry and partial order reduction

$[x = 0]$		
T1: $x := 1$	T2: $r := x$	T3: $r := x$



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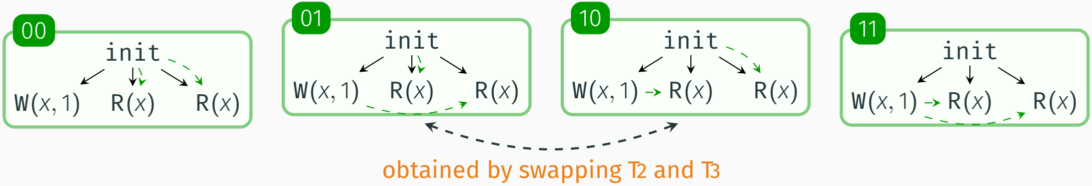
$[x = 0]$

Key Idea: Identify symmetries on the execution graphs



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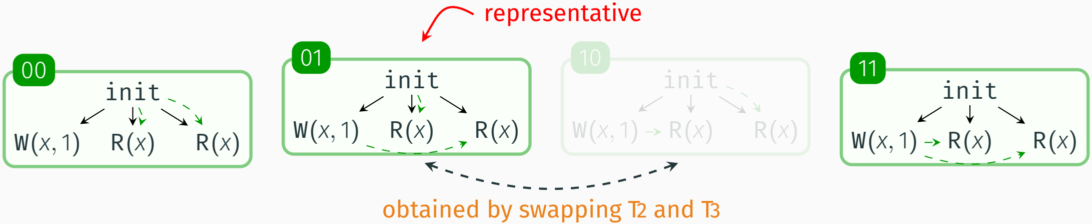
Key Idea: Identify symmetries on the execution graphs

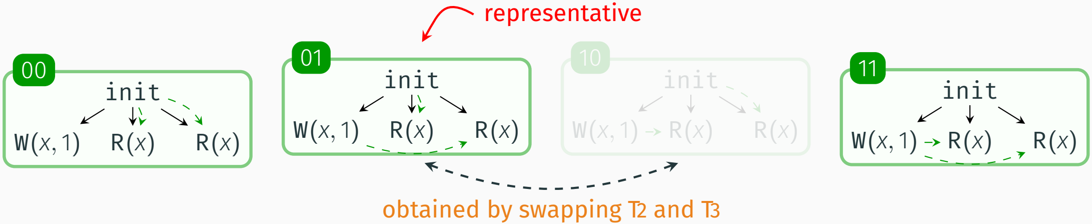


Combining SR and POR

[PLDI'24] SPORE: Combining symmetry and partial order reduction

$[x = 0]$

Key Idea: Identify symmetries on the execution graphs
Only generate representative graphs



Combining SR and POR

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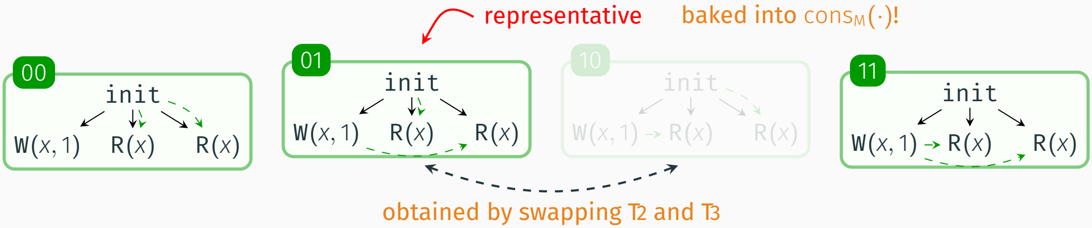

Combining SR and POR

[PLDI'24] SPORE: Combining symmetry and partial order reduction

$[x = 0]$

Key Idea: Identify symmetries on the execution graphs

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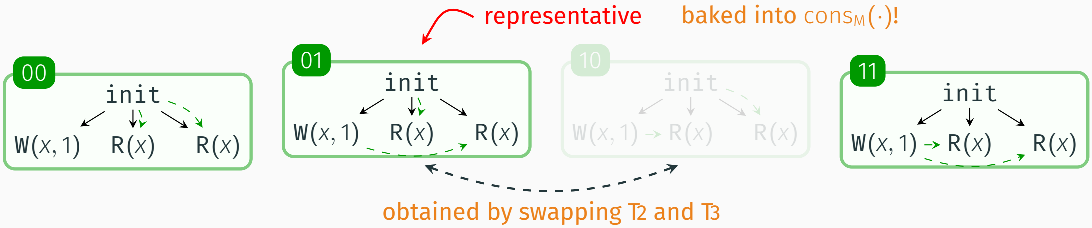

There are many types of symmetries

$\rightsquigarrow$ these can be incorporated into $\mathsf{cons}_M(\cdot)$

Internal symmetries example: Michael-Scott queue

```
enqueue(v) ≜
  node := malloc(...)
  node.value := v
  node.next := NULL
  do
    t := tail
    next := t.next
    if (t ≠ tail)  continue
    if (next ≠ NULL)
      CAS(tail, t, next)
      continue
  while (¬CAS(t.next, next, node))
  CAS(tail, t, node)
```

Internal symmetries example: Michael-Scott queue

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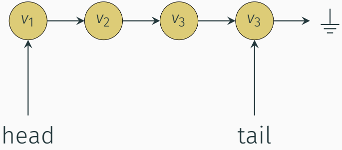

Internal symmetries example: Michael-Scott queue

T1 ➡

```
enqueue(v) ≜
  node := malloc(...)
  node.value := v
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  do
    t := tail
    next := t.next
    if (t ≠ tail) continue
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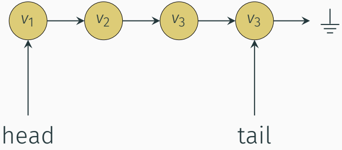
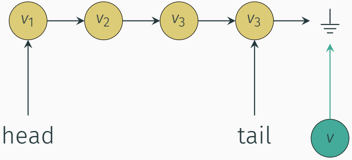


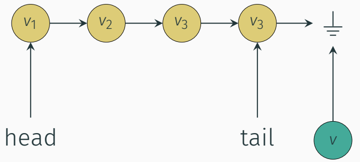
Internal symmetries example: Michael-Scott queue

```
   enqueue(v) ≜
T1   node := malloc(...)
     node.value := v
     node.next := NULL
     do
       t := tail
       next := t.next
       if (t ≠ tail) continue
       if (next ≠ NULL)
         CAS(tail, t, next)
         continue
     while (¬CAS(t.next, next, node))
     CAS(tail, t, node)
```



Internal symmetries example: Michael-Scott queue

enqueue(v) $\triangleq$
  $node$:= malloc(...)
  $node.value$:= v
  $node.next$:= NULL
  do
T1 ➡ t := $\underline{tail}$
    $next$:= $t.next$
    if ($t \neq \underline{tail}$) **continue**
    if ($next \neq$ NULL)
      CAS($\underline{tail}$, t, $next$)
      continue
  while ($\neg$CAS($t.next$, $next$, $node$))
  CAS($\underline{tail}$, t, $node$)



Internal symmetries example: Michael-Scott queue

T1 ➡ (at line $t := \underline{tail}$)

```
enqueue(v) ≜
  node := malloc(...)
  node.value := v
  node.next := NULL
  do
    t := tail
    next := t.next
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    if (next ≠ NULL)
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      continue
  while (¬CAS(t.next, next, node))
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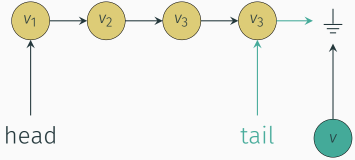

Internal symmetries example: Michael-Scott queue

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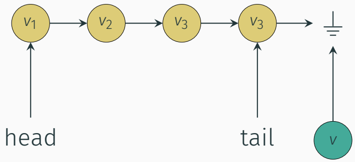
    if (next ≠ NULL)
      CAS(tail, t, next)
      continue
  while (¬CAS(t.next, next, node))
  CAS(tail, t, node)
```

T1 → (at `while (¬CAS(t.next, next, node))`)



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T1 →  while (¬CAS(t.next, next, node))
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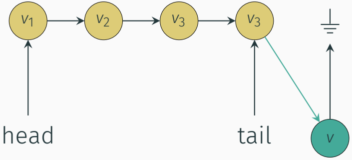

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  do
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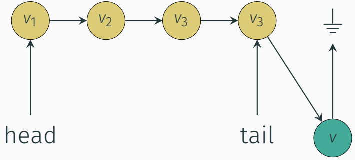
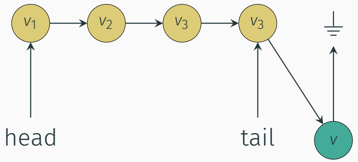
    next := t.next
    if (t ≠ tail) continue
    if (next ≠ NULL)
      CAS(tail, t, next)
      continue
  while (¬CAS(t.next, next, node))
T1 → CAS(tail, t, node)
```



Internal symmetries example: Michael-Scott queue

```
enqueue(v) ≜
T2 → node := malloc(...)
     node.value := v
     node.next := NULL
     do
        t := tail
        next := t.next
        if (t ≠ tail) continue
        if (next ≠ NULL)
           CAS(tail, t, next)
           continue
     while (¬CAS(t.next, next, node))
T1 → CAS(tail, t, node)
```



Internal symmetries example: Michael-Scott queue

```
    enqueue(v) ≜
T2 ➡  node := malloc(...)
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      do
        t := tail
        next := t.next
        if (t ≠ tail) continue
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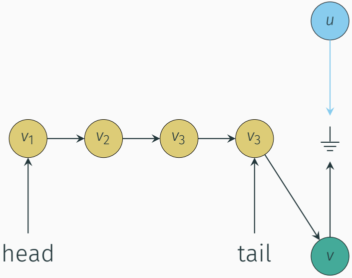
          CAS(tail, t, next)
          continue
      while (¬CAS(t.next, next, node))
T1 ➡  CAS(tail, t, node)
```



Internal symmetries example: Michael-Scott queue

enqueue(v) $\triangleq$

  $node$:= malloc(...)

  $node.value$:= v

  $node.next$:= NULL

  do

T2 → t := $\underline{tail}$

    $next$:= $t.next$

    if ($t \neq \underline{tail}$) **continue**

    if ($next \neq$ NULL)

      CAS($\underline{tail}$, t, $next$)

      continue

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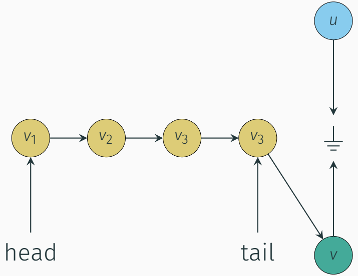

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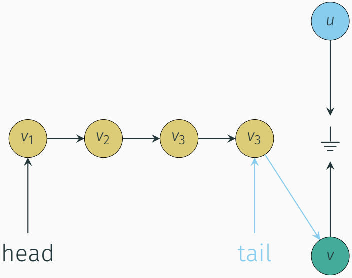
T1  CAS(tail, t, node)
```



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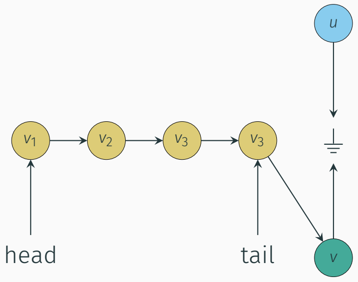

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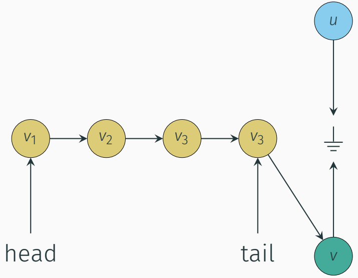
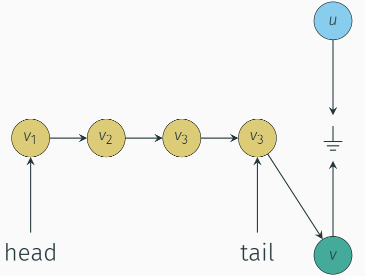
T2   CAS($\underline{tail}$, t, $next$)
      continue
  while ($\neg$CAS($t.next$, $next$, $node$))
T1 CAS($\underline{tail}$, t, $node$)



Contention on tail hinders verification!

Internal symmetries example: Michael-Scott queue

```
enqueue(v) ≜
  node := malloc(...)
  node.value := v
  node.next := NULL
  do
    t := tail
    next := t.next
    if (t ≠ tail) continue
    if (next ≠ NULL)
      CAS(tail, t, next)      ← T2
      continue
  while (¬CAS(t.next, next, node))
  CAS(tail, t, node)          ← T1
```



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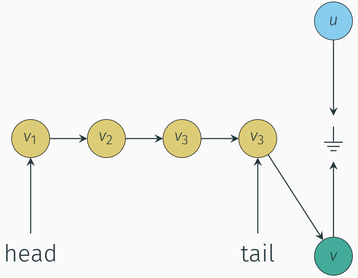

Contention on tail hinders verification! → $K!$ overhead for K threads

Observe: The conflicting operations are identical and idempotent

GenMC leverages idempotent operations by splitting them to *main* and *helping*

⇝ this requires annotating the input program

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Is this sound?

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Is this sound?

$x = y = 0$

T1:	T2:	T3:
$y := 1$ CAS$(x, 0, 1)$ (main)	CAS$(x, 0, 1)$ (helping)	`if` $(x = 1)$ `assert`$(y = 1)$

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GenMC presents **sufficient conditions** for leveraging idempotent operations

⇝ *main* and *helping* can be functions …

⇝ but they have to satisfy certain conditions (e.g., induce same synchronization)

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Internal symmetries can also be leveraged in non-symmetric programs!

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$$[data = flag = 0]$$

$data := 42$ $flag := 1$	$\parallel$	`if` $(flag = 1)$ `assert`$(data = 42)$

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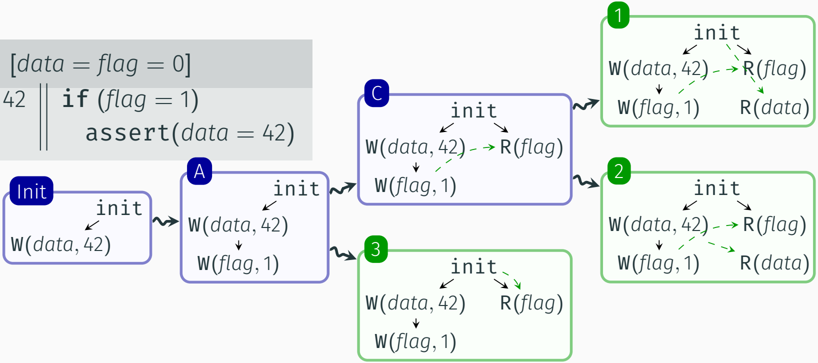

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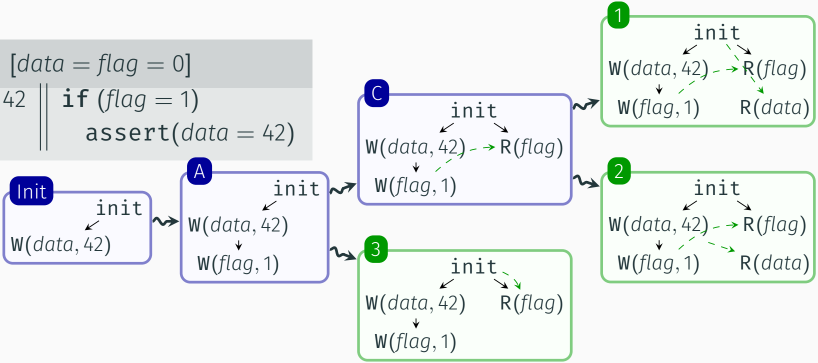

Naive “solution”:

- Assume symmetric state space
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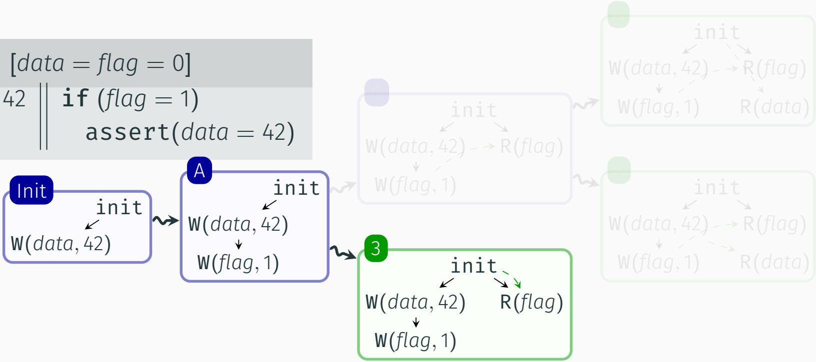

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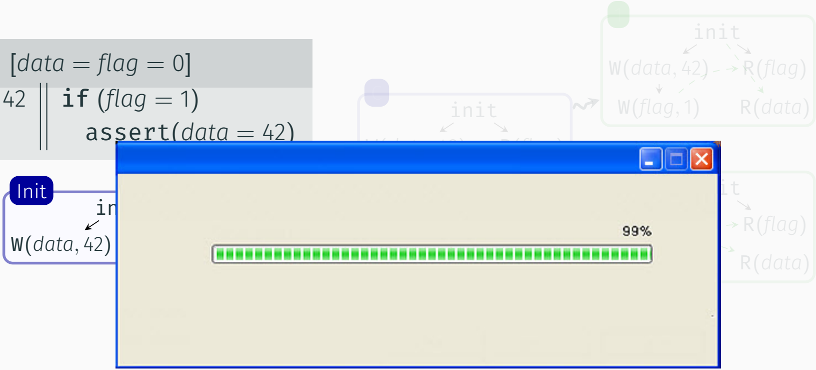

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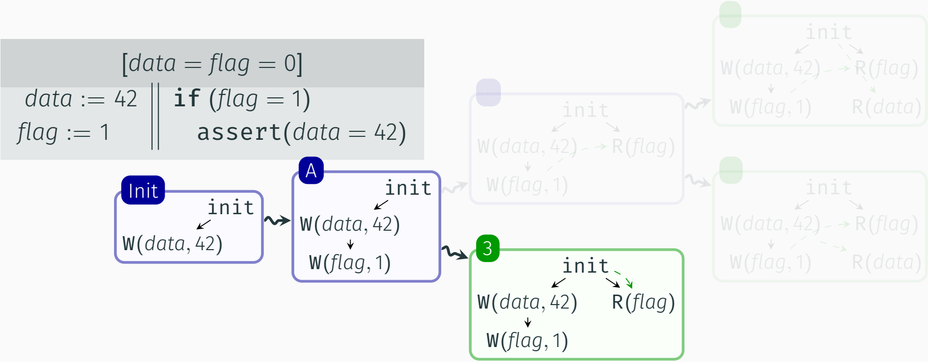

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Our Idea: Monte Carlo Simulation before verification

- Take random samples (assuming symmetric space)
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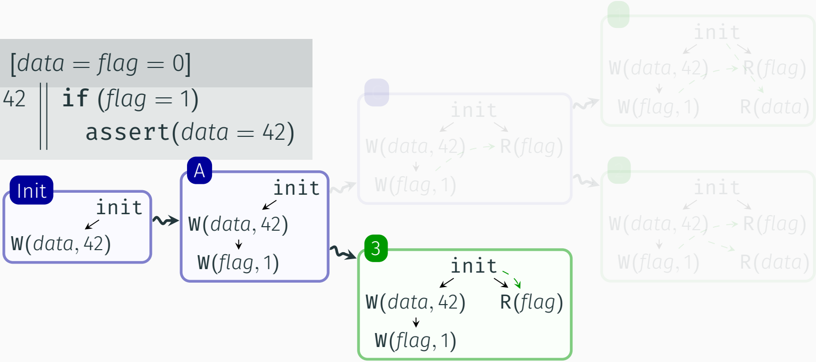

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$$[x = 0]$$

$$\begin{array}{l} a := x \\ \textbf{if}\ (a > 0)\ b := x \end{array} \;\Big\|\; x := 1 \;\Big\|\; x := 2$$

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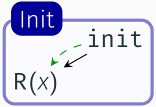

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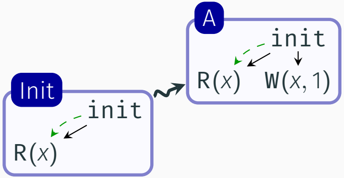

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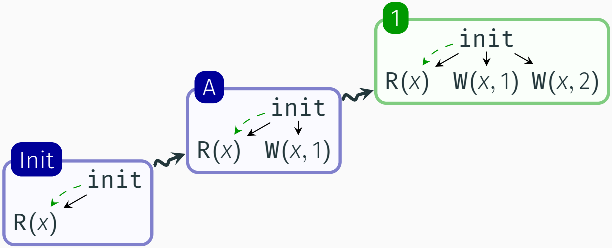

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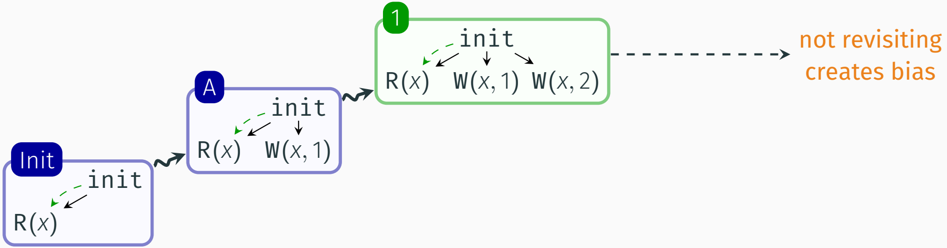

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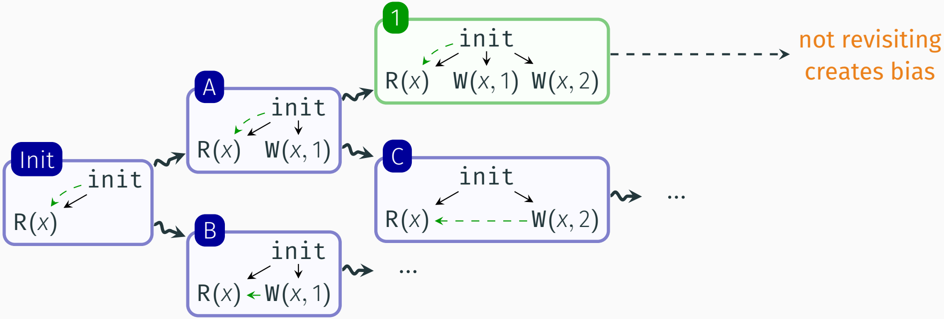

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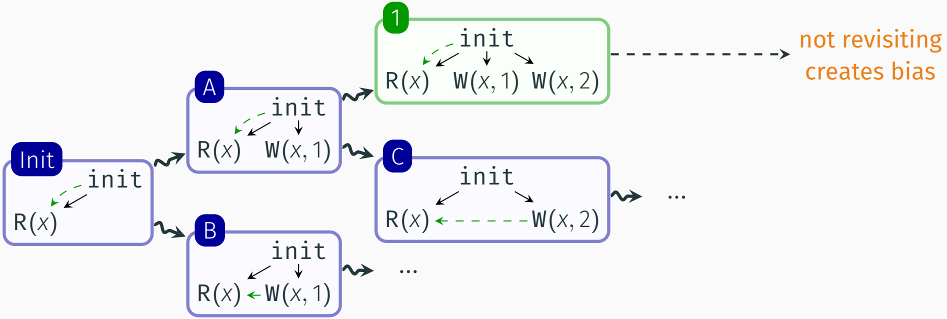

Problem: When to perform a revisit?

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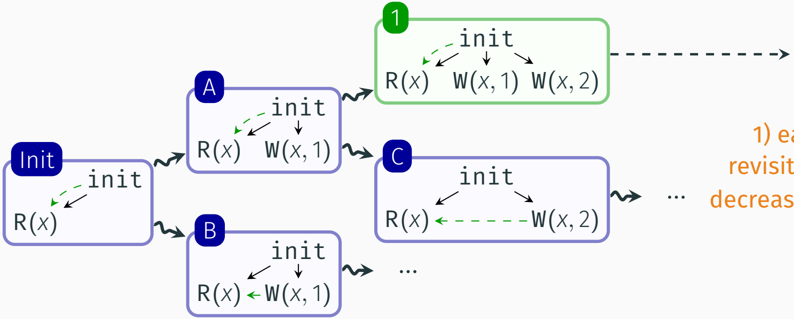

not revisiting creates bias

1) each read gets one revisit: revisit probability for later writes decreases exponentially ($p(1-p)\ldots$)

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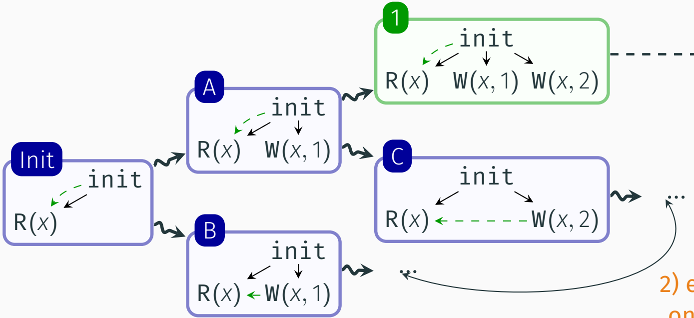

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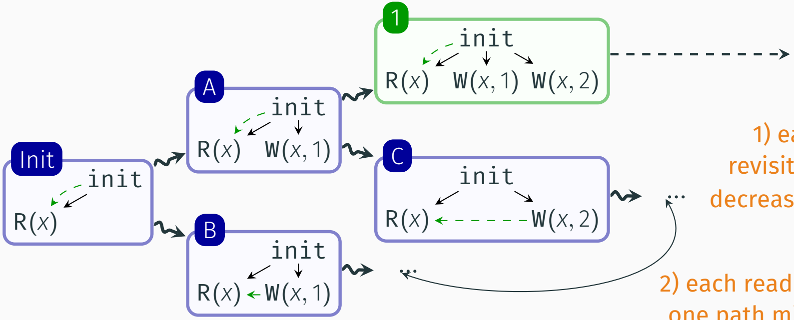

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Our Solution: No revisits — random scheduler that prioritizes writes over reads

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Bounded exploration and POR

$[x = y = 0]$		
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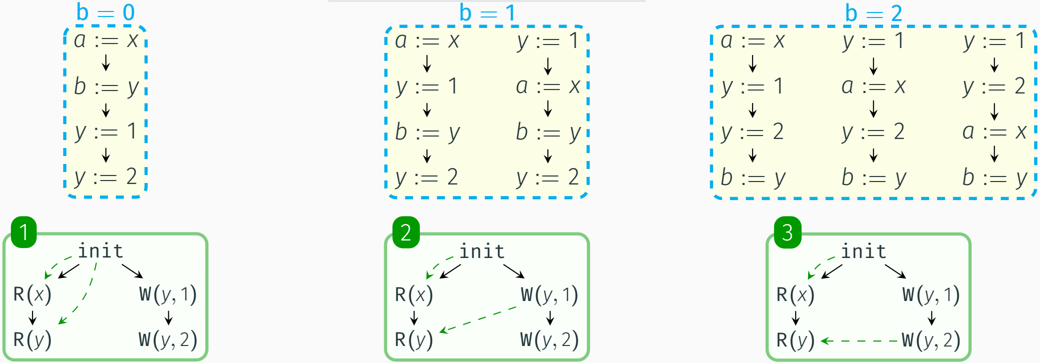
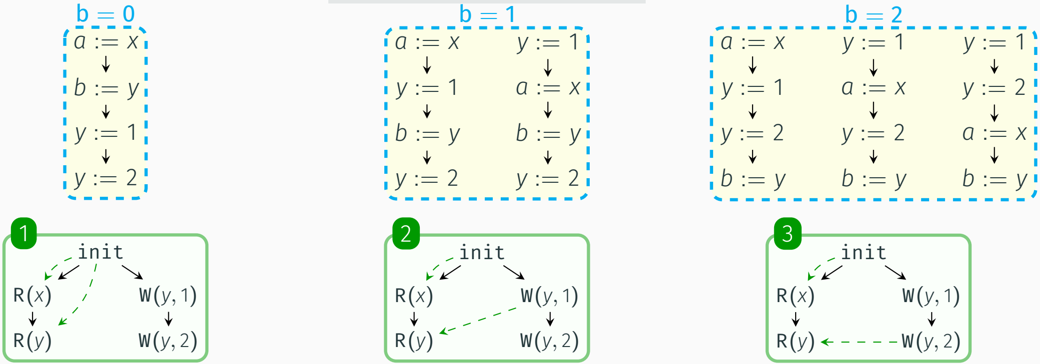


Bounded exploration and POR

$$[x = y = 0]$$

$$\begin{array}{r||l} a := x & y := 1 \\ b := y & y := 2 \end{array}$$



Goal: Only explore graphs $G \in [\![P]\!]$ where exists $t \in \mathrm{trace}(G)$ s.t. $B(t) \leq K$

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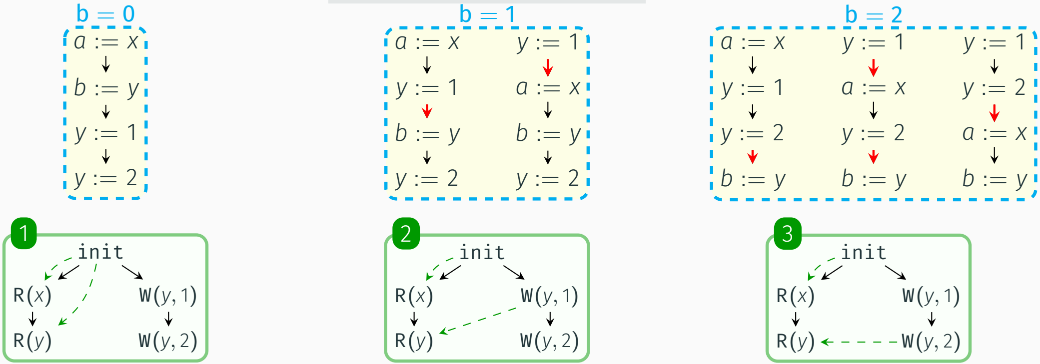

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here: round-robin rounds

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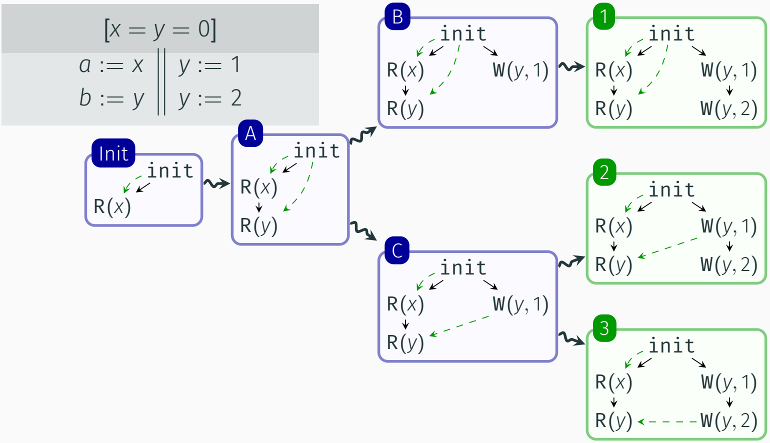
Bounded POR



[x = y = 0]
a := x || y := 1
b := y || y := 2
Init
init
R(x)
A
init
R(x)
R(y)
B
init
R(x)
W(y, 1)
R(y)
C
init
R(x)
W(y, 1)
R(y)
1
init
R(x)
W(y, 1)
R(y)
W(y, 2)
2
init
R(x)
W(y, 1)
R(y)
W(y, 2)
3
init
R(x)
W(y, 1)
R(y)
W(y, 2)

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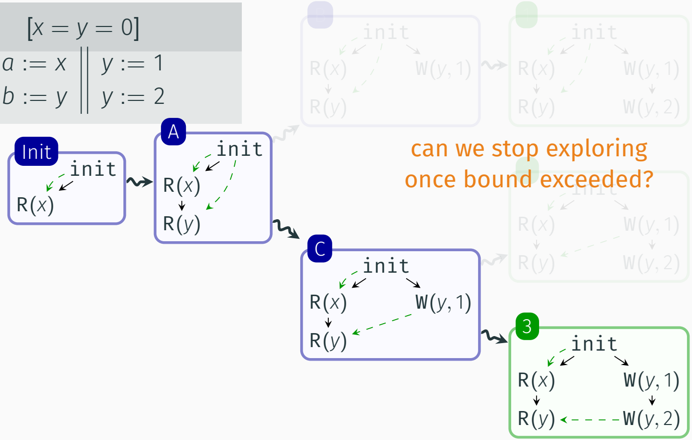

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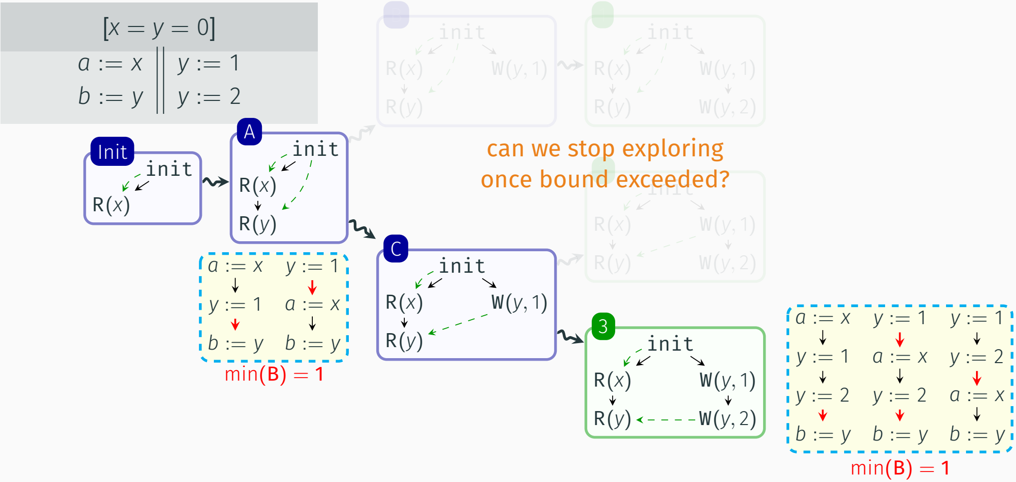

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a := x || y := 1
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Init
init
R(x)
A
init
R(x)
R(y)
a := x y := 1
y := 1 a := x
b := y b := y
min(B) = 1
C
init
R(x) W(y, 1)
R(y)
can we stop exploring
once bound exceeded?
3
init
R(x) W(y, 1)
R(y) W(y, 2)
a := x y := 1 y := 1
y := 1 a := x y := 2
y := 2 y := 2 a := x
b := y b := y b := y
min(B) = 1

Bounded POR

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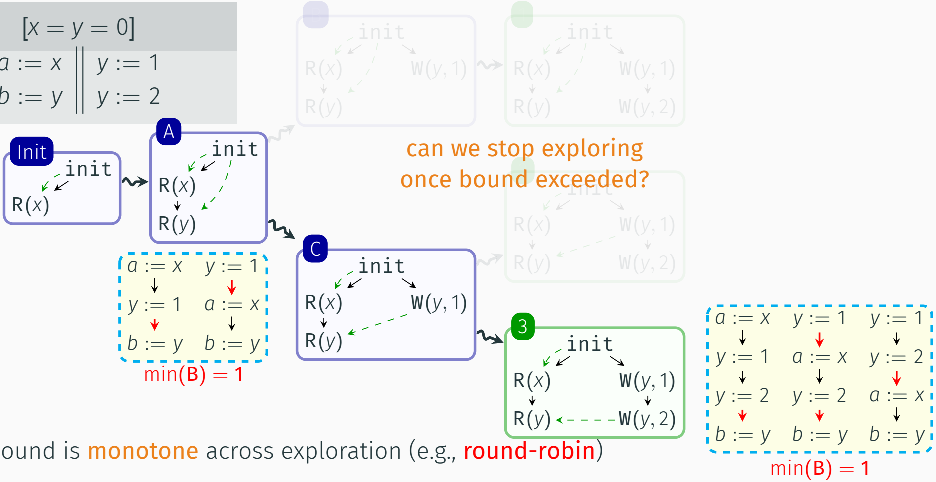
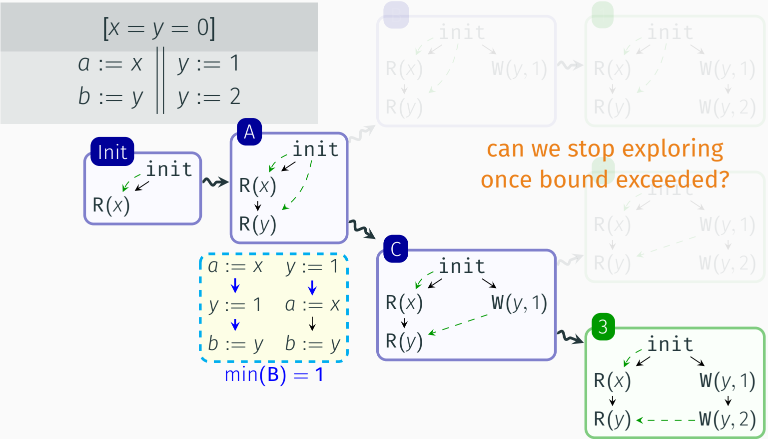
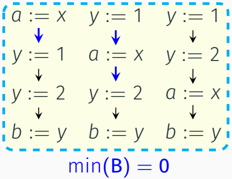


can we stop exploring once bound exceeded?

Yes, if bound is monotone across exploration (e.g., round-robin)

Bounded POR





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$\rightsquigarrow$ **context bounding**: intermediate graphs might have bound $\leq T + K - 2$

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