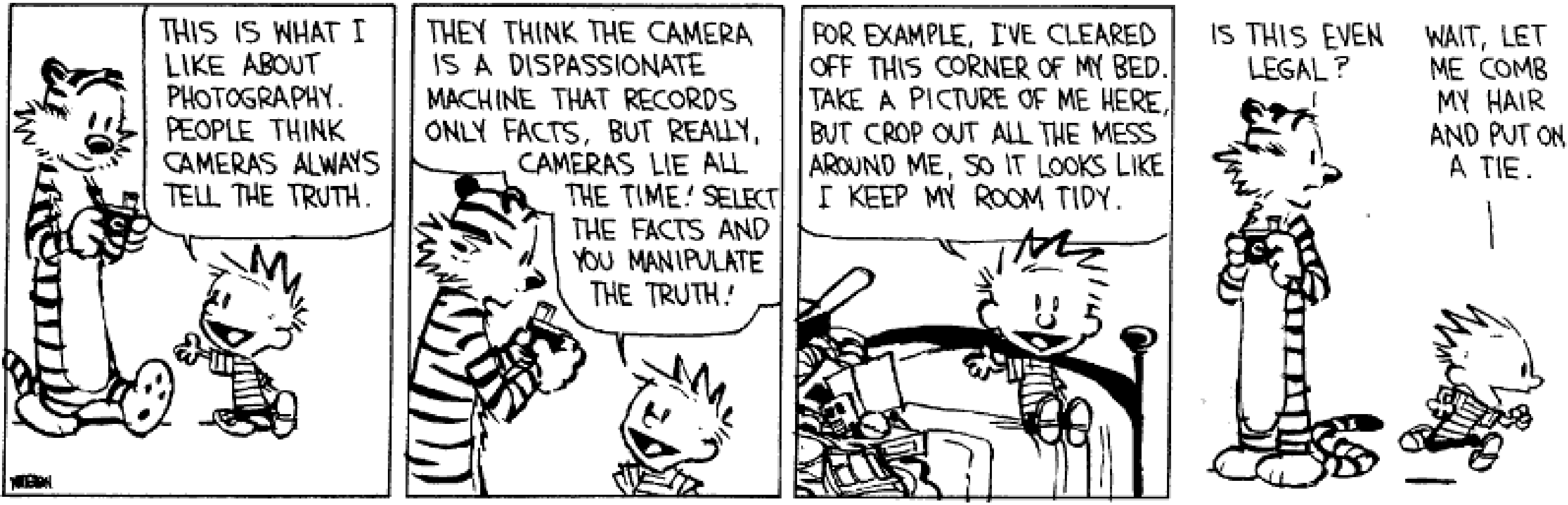


Having a BLAST with SLAM

Topic: Software Model Checking via Counter-Example Guided Abstraction Refinement

- There are easily two dozen SLAM/BLAST/MAGIC papers; I will skim.

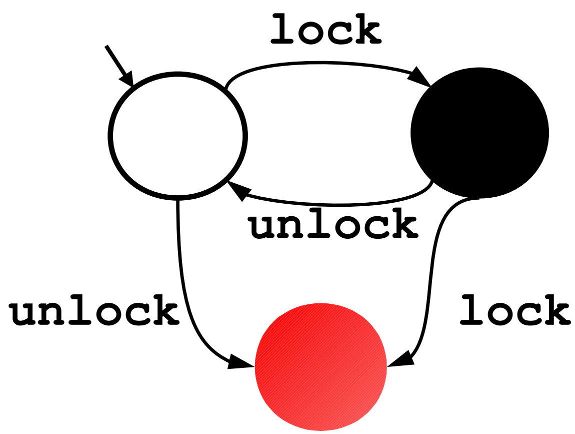
SLAM Overview

- INPUT: Program *and* Specification
  - Standard C Program (pointers, procedures)
  - Specification = Partial Correctness
    - Given as a finite state machine (typestate)
    - “I use locks correctly”, *not* “I am a webserver”
- OUTPUT: Verified *or* Counterexample
  - Verified = program does not violate spec
    - Can come with proof!
  - Counterexample = concrete bug instance
    - A path through the program that violates the spec

Take-Home Message

- **SLAM** is a **software model checker**. It **abstracts** C programs to **boolean programs** and model-checks the boolean programs.
- No errors in the boolean program implies no errors in the original.
- An error in the boolean program **may** be a real bug. Or SLAM may **refine** the abstraction and start again.

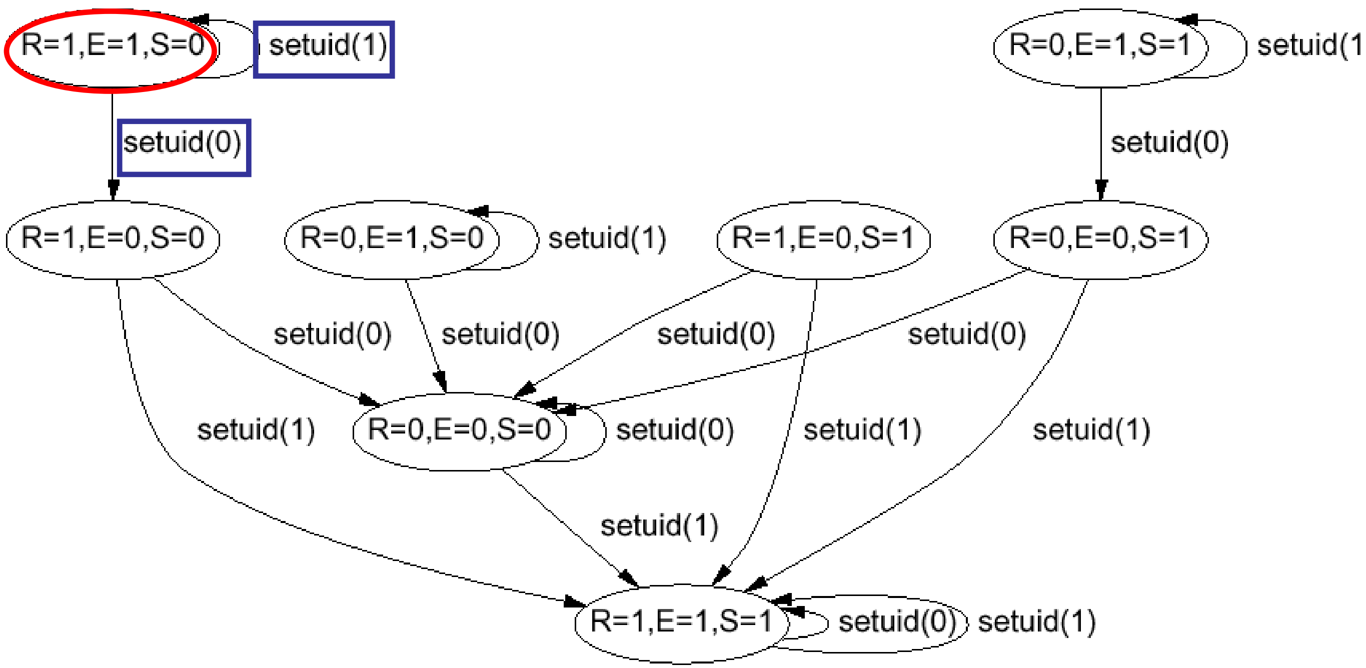
Property 1: Double Locking



"An attempt to re-acquire an acquired lock or release a released lock will cause a ***deadlock****."*

Calls to **lock** and **unlock** must **alternate**.

Property 2: Drop Root Privilege

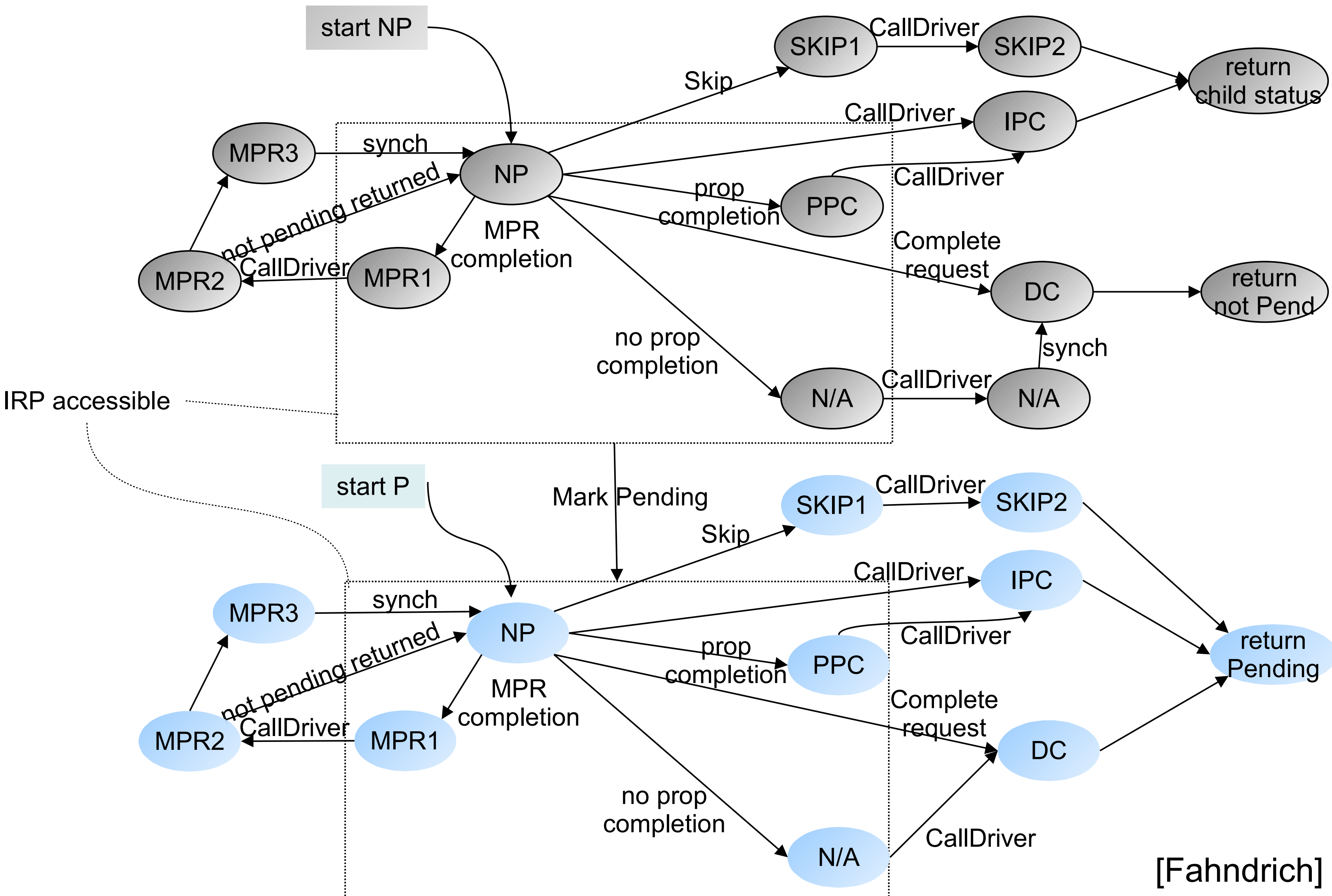


[Chen-Dean-Wagner '02]

"User applications must not run with root privilege"

When **execv** is called, must have **suid ≠ 0**

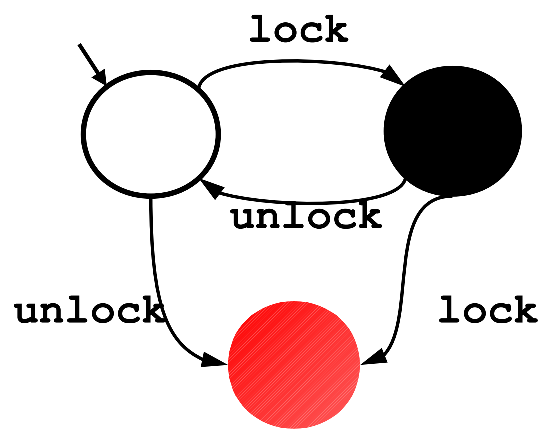
Property 3 : IRP Handler



[Fahndrich]

Example SLAM Input

```
Example ( ) {
1: do{
        lock();
        old = new;
        q = q->next;
2:      if (q != NULL){
3:          q->data = new;
            unlock();
            new ++;
        }
4: } while(new != old);
5:    unlock ();
      return;
}
```

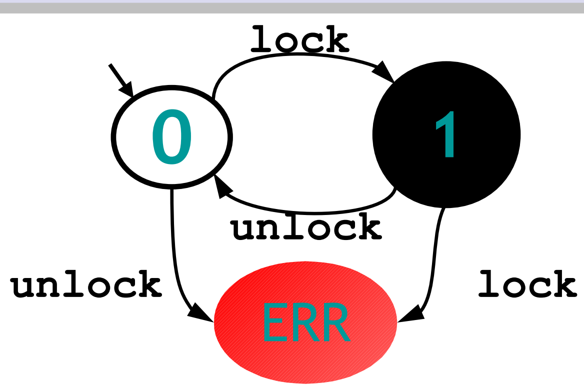


SLAM in a Nutshell

```
SLAM(Program p, Spec s) =                          // program
 Program q = incorporate_spec(p,s);                // slic
 mutable PredicateSet abs = { };
 while true do
   BooleanProgram b = abstract(q,abs);             // c2bp
   match model_check(b) with                       // bebop
    | No_Error → printf("no bug"); exit(0)
    | Counterexample(c) →
        if is_valid_path(c, p) then                // newton
          printf("real bug"); exit(1)
        else
          abs ← abs ∪ new_preds(c)                 // newton
done
```

Incorporating Specs

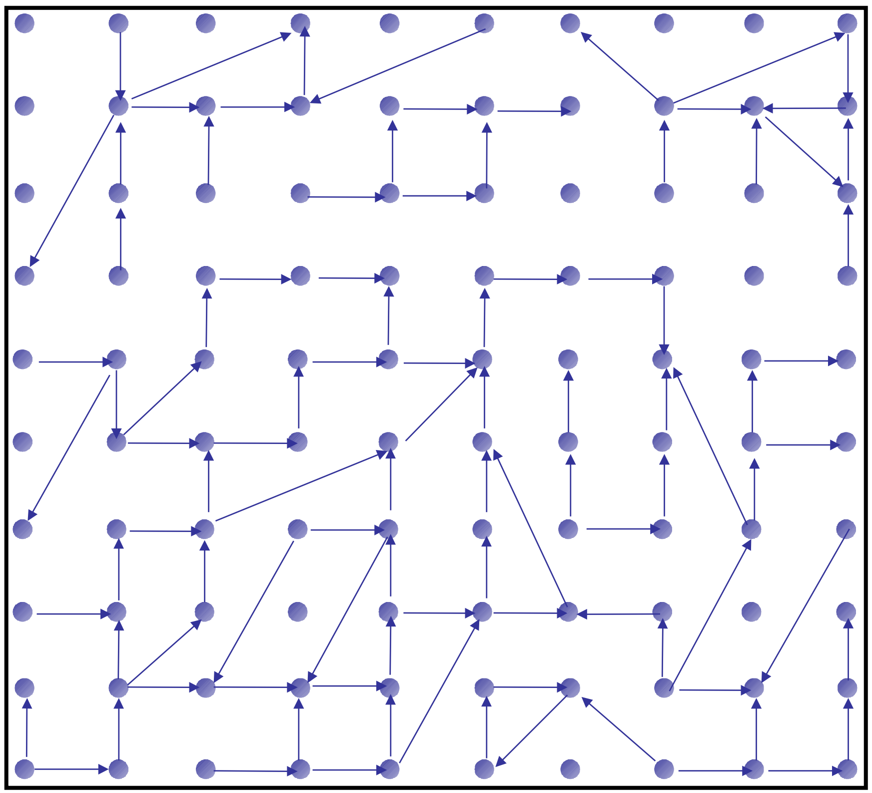
```
Example ( ) {
1: do{
      lock();
      old = new;
      q = q->next;
2:    if (q != NULL){
3:      q->data = new;
        unlock();
        new ++;
      }
4: } while(new != old);
5:  unlock ();
    return;
}
```




```
Example ( ) {
1: do{
        if L=1 goto ERR;
        else L=1;
        old = new;
        q = q->next;
2:      if (q != NULL){
3:          q->data = new;
            if L=0 goto ERR;
            else L=0;
            new ++;
        }
4: } while(new != old);
5:   if L=0 goto ERR;
     else L=0;
     return;
ERR: abort();
}
```

Original program violates spec iff new program reaches ERR

Program As
Labeled Transition System



pc	$\mapsto$ 3
lock	$\mapsto$ ●
old	$\mapsto$ 5
new	$\mapsto$ 5
q	$\mapsto$ 0x133a

```
3:  unlock();
    new++;
4:} …
```

pc	$\mapsto$ 4
lock	$\mapsto$ O
old	$\mapsto$ 5
new	$\mapsto$ 6
q	$\mapsto$ 0x133a

```
Example ( ) {
1: do {
      lock();
      old = new;
      q = q->next;
2:    if (q != NULL){
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          unlock();
          new ++;
      }
4: } while(new != old);
5:   unlock ();
     return; }
```
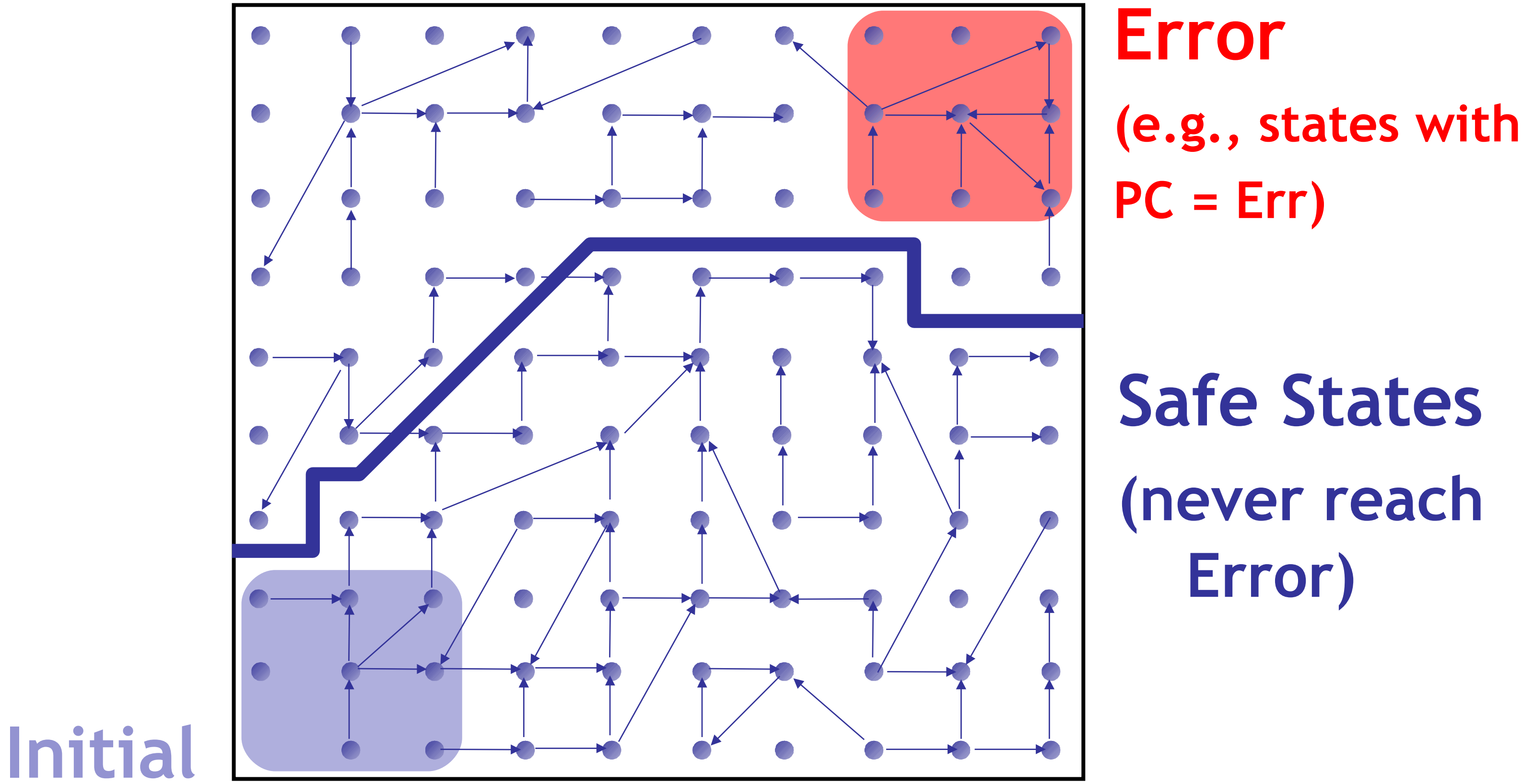

The Safety Verification Problem



Is there a **path** from an **initial** to an **error** state ?

Problem: Infinite state graph (old=1, old=2, old=…)

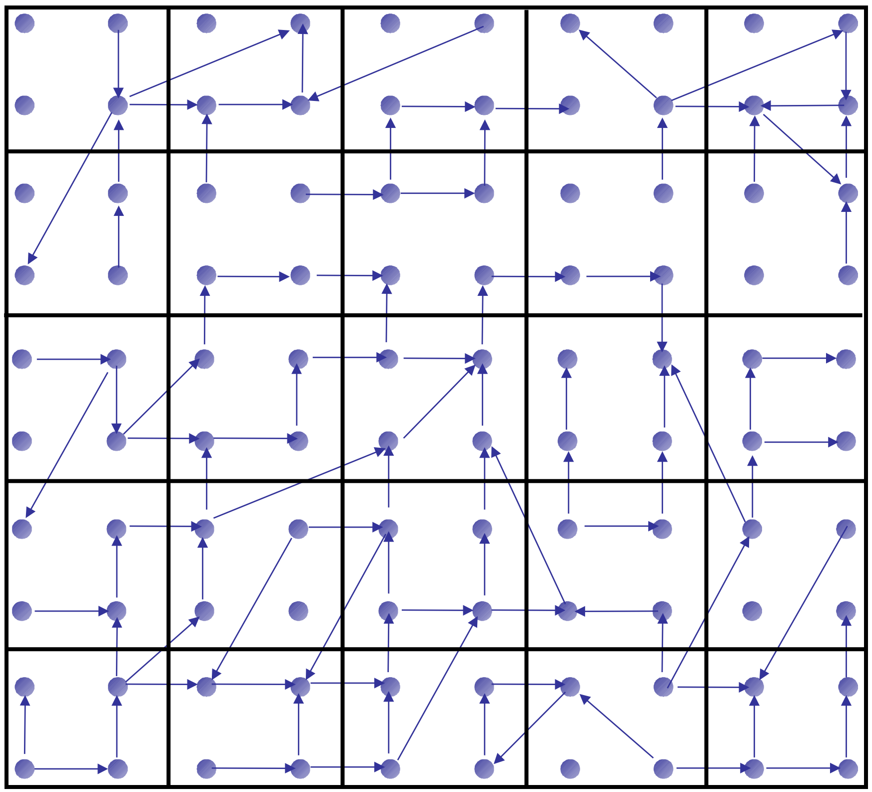
Solution : **Set** of states $\simeq$ logical **formula**

Representing [Sets of States] as *Formulas*

$[F]$ states satisfying F $\{s \mid s \models F\}$	F FO fmla over prog. vars
$[F_1] \cap [F_2]$	$F_1 \wedge F_2$
$[F_1] \cup [F_2]$	$F_1 \vee F_2$
$\overline{[F]}$	$\neg F$
$[F_1] \subseteq [F_2]$	$F_1 \Rightarrow F_2$

i.e. $F_1 \wedge \neg F_2$ unsatisfiable

Idea 1: Predicate Abstraction



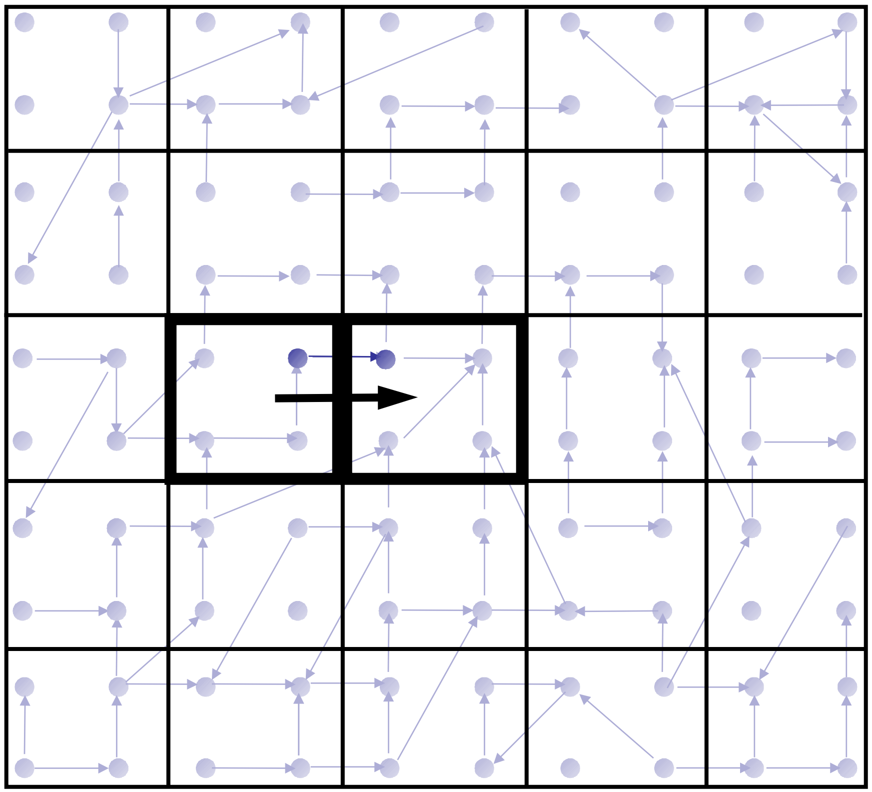
- **Predicates** on program state:

  lock *(i.e., lock=true)*

  old = new

- States satisfying **same** predicates are **equivalent**
  - **Merged** into one **abstract state**
- #abstract states is **finite**
  - **Thus model-checking the abstraction will be feasible!**

Abstract States and Transitions



State

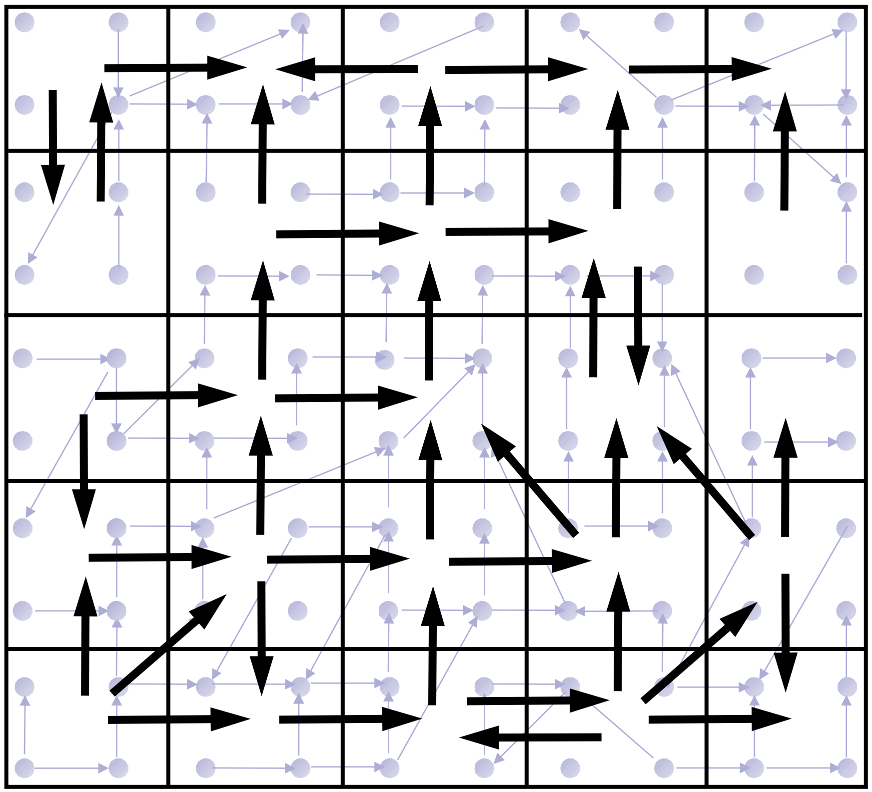
pc $\mapsto$ 3	*pc* $\mapsto$ 4
lock $\mapsto$ ●	lock $\mapsto$ ○
old $\mapsto$ 5	old $\mapsto$ 5
new $\mapsto$ 5	new $\mapsto$ 6
q $\mapsto$ 0x133a	q $\mapsto$ 0x133a

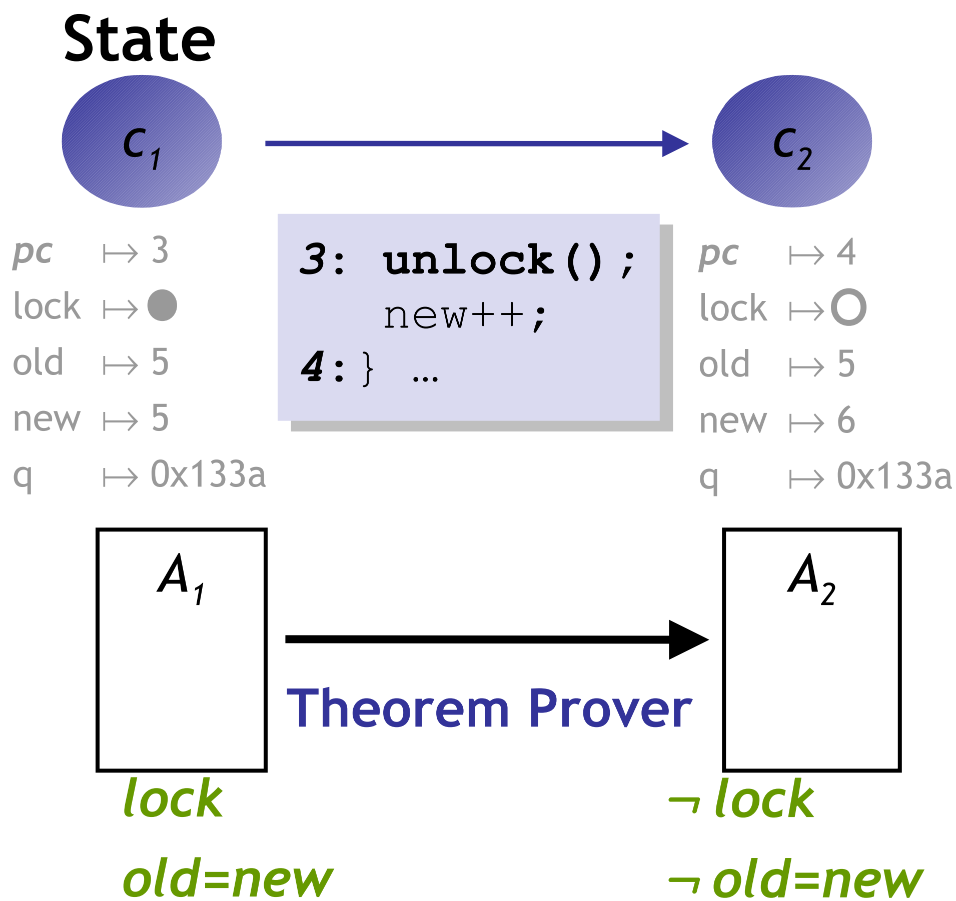
```
3: unlock();
   new++;
4:} …
```

Theorem Prover

lock	¬ *lock*
old=new	¬ *old=new*

Abstraction

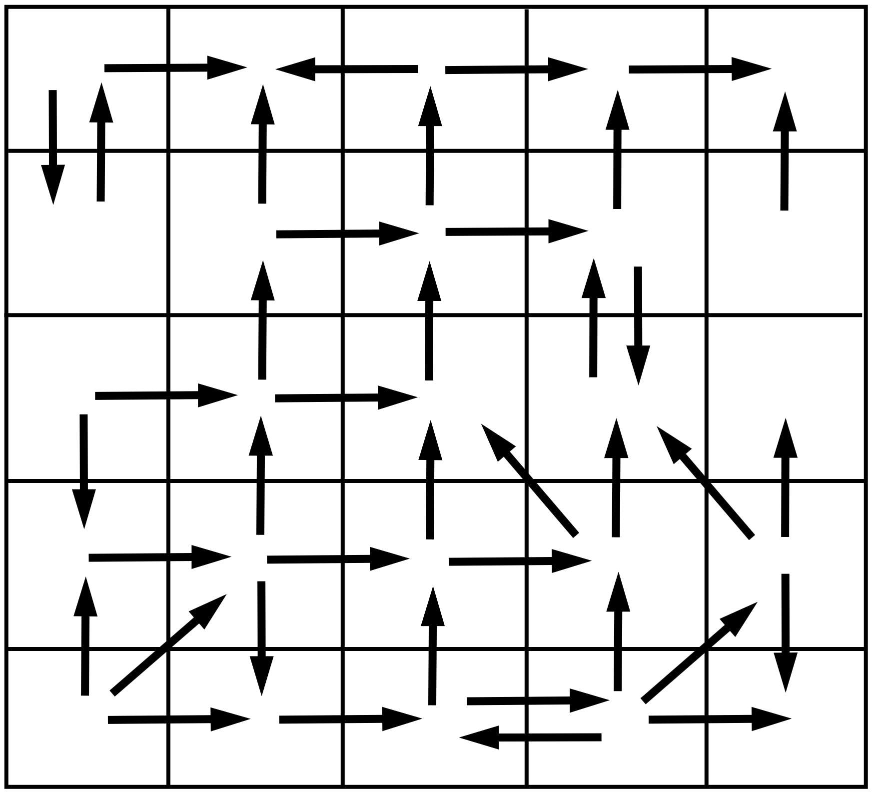


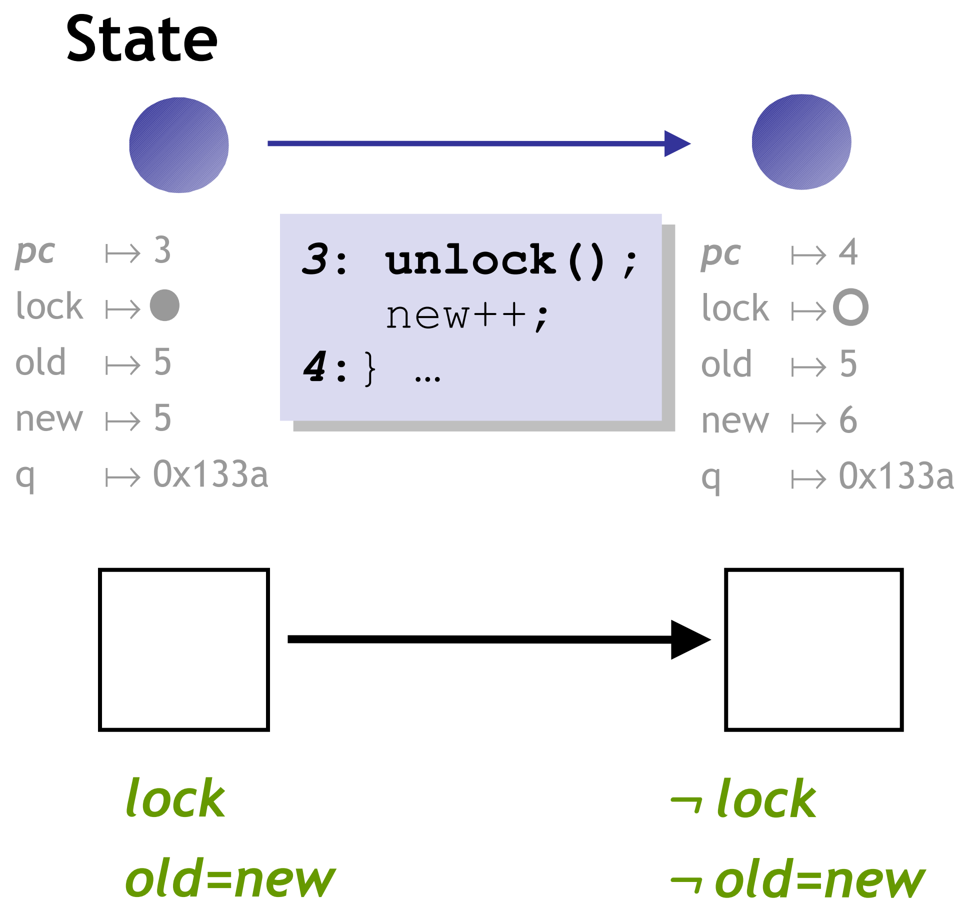


Existential Lifting

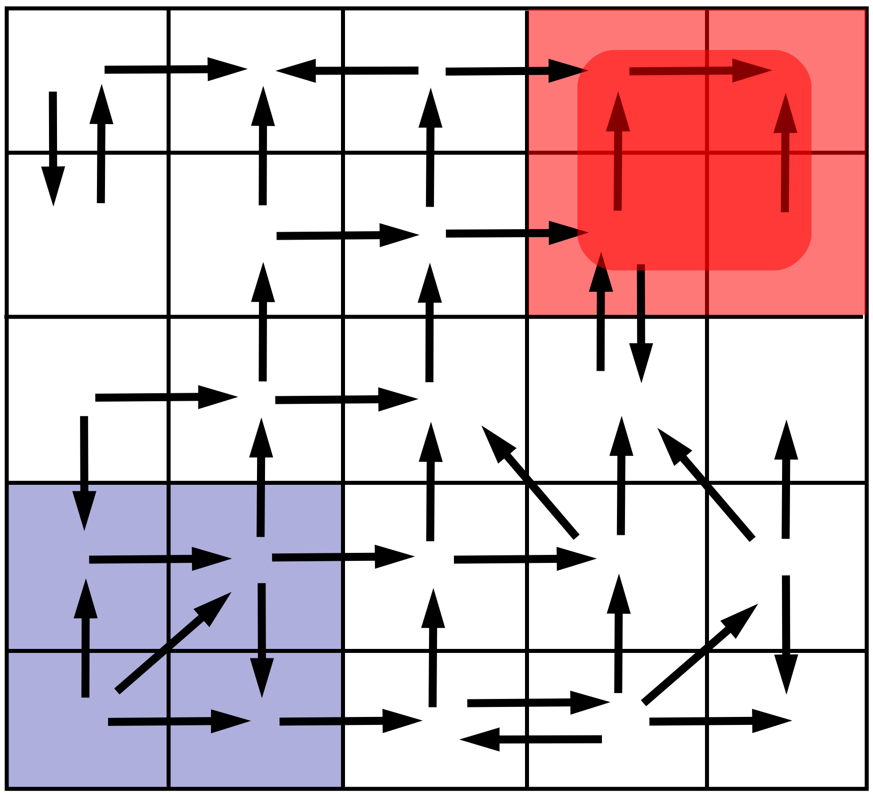
(i.e., $A_1 \rightarrow A_2$ iff $\exists c_1 \in A_1.\ \exists c_2 \in A_2.\ c_1 \rightarrow c_2$)

Abstraction





Analyze Abstraction



Analyze finite graph

Over Approximate:

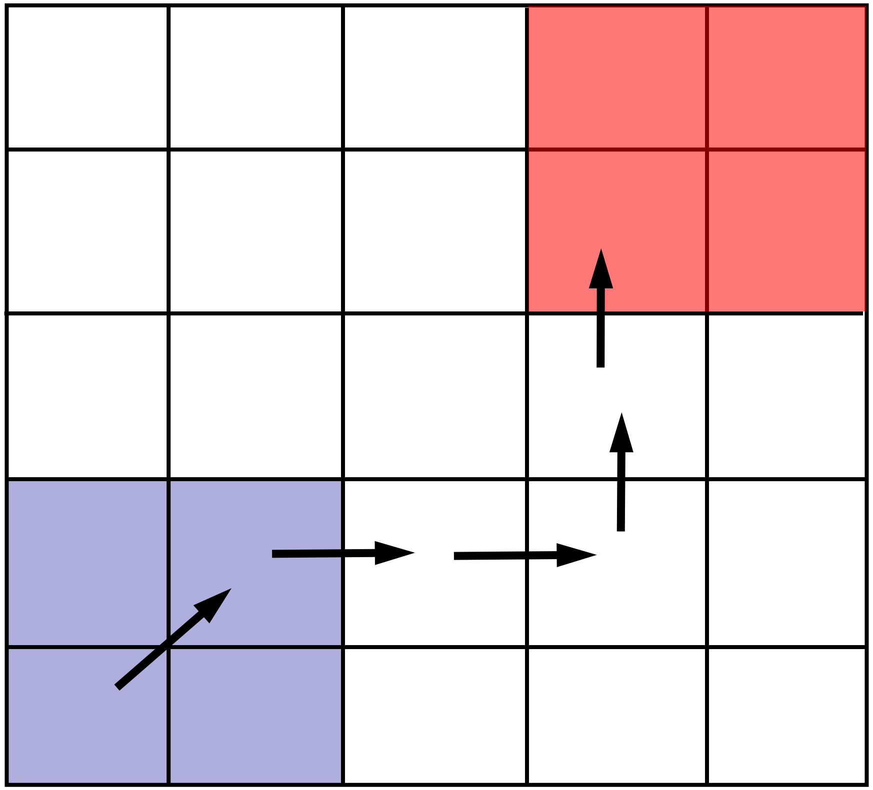
Safe $\Rightarrow$ System Safe

No **false negatives**

Problem

Spurious **counterexamples**

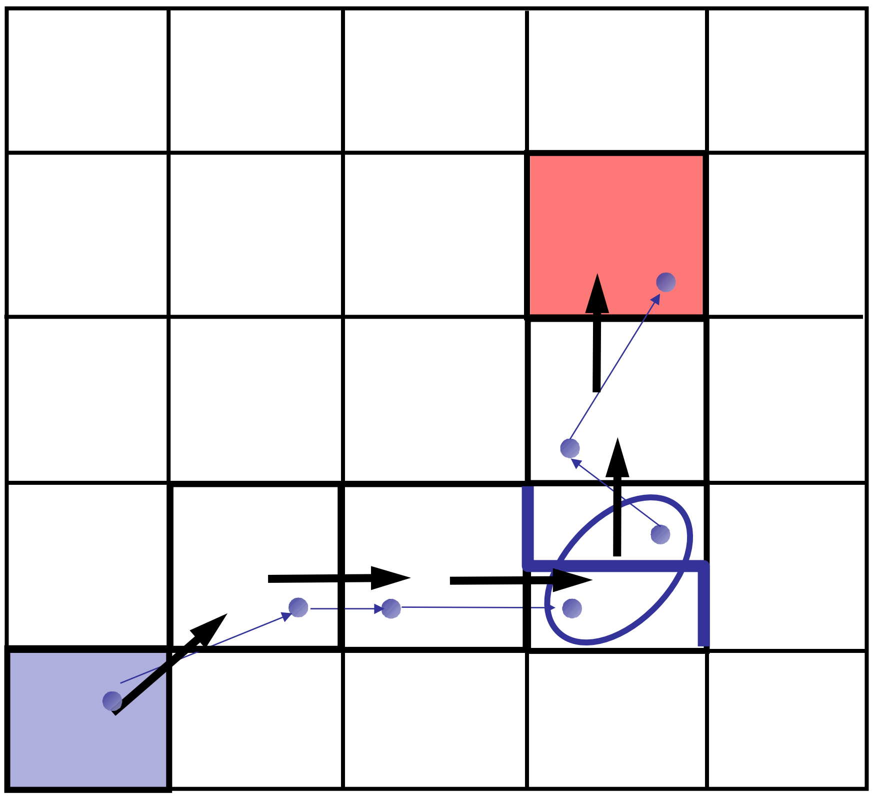
Idea 2: Counterex.-Guided Refinement



Solution

Use spurious **counterexamples** to **refine** abstraction!

Idea 2: Counterex.-Guided Refinement



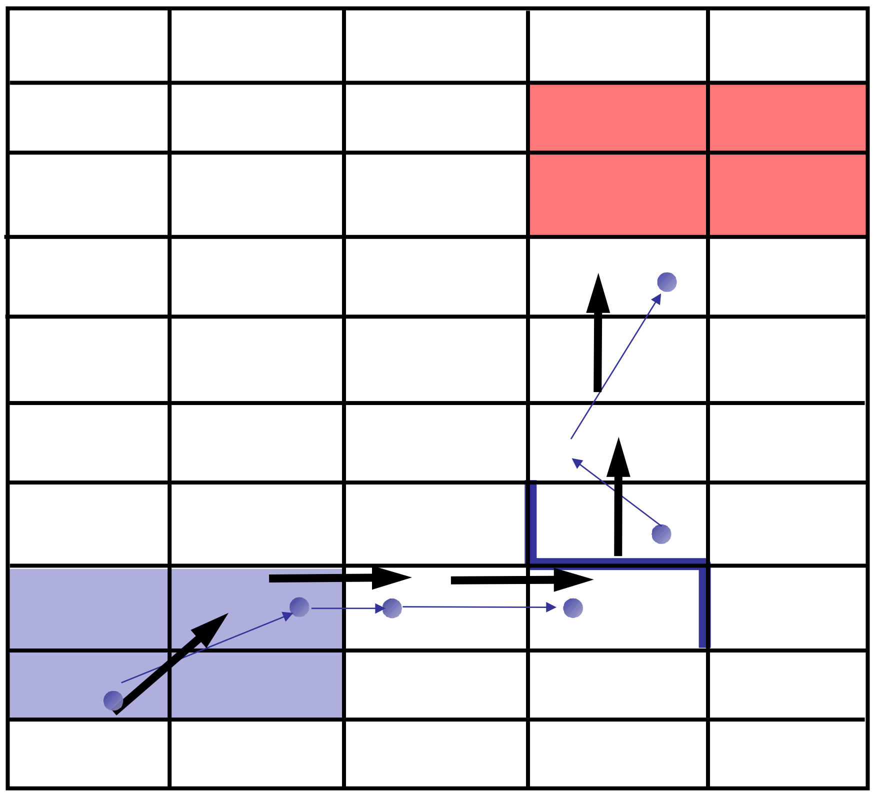
Solution

Use spurious **counterexamples** to **refine** abstraction

1. **Add predicates** to distinguish states across **cut**
2. Build **refined** abstraction

Imprecision due to **merge**

Iterative Abstraction-Refinement



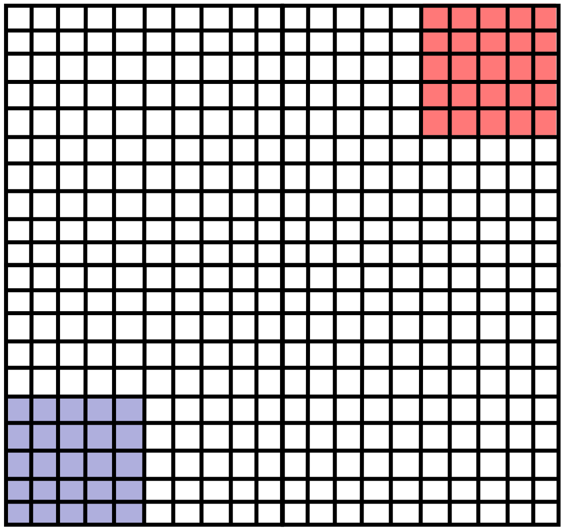
[Kurshan et al 93] [Clarke et al 00]
[Ball-Rajamani 01]

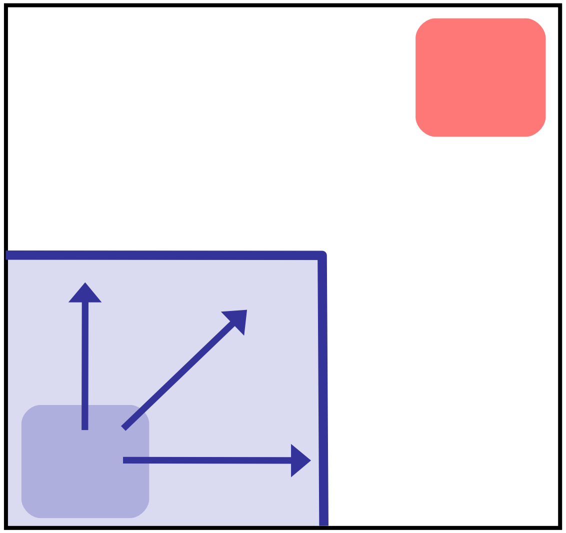
Solution

Use spurious **counterexamples** to **refine** abstraction

1. Add predicates to distinguish states across **cut**
2. Build **refined** abstraction
   -eliminates counterexample
3. **Repeat** search
   Untill real counterexample or system proved safe

Problem: Abstraction is Expensive





Reachable

Problem

#abstract states = $2^{\#predicates}$

Exponential Thm. Prover queries

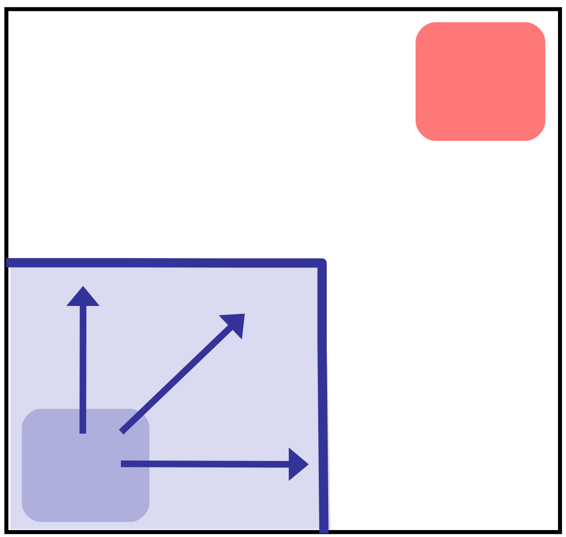
Observe

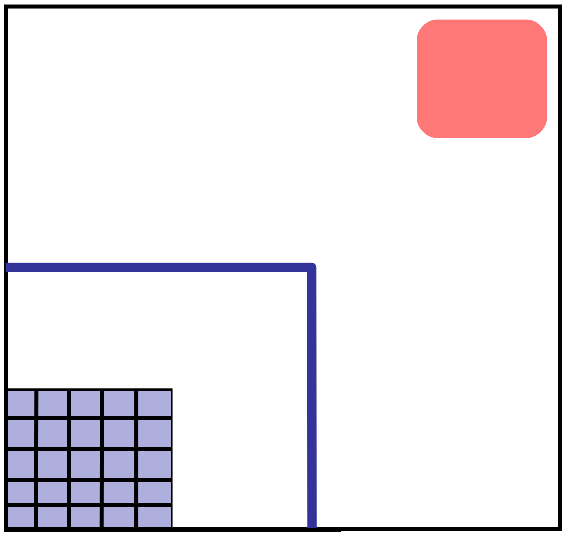
Fraction of state space reachable

#Preds ~ 100's, #States ~ 2^{100} ,

#Reach ~ 1000's

Solution1: Only Abstract Reachable States





Safe

Problem

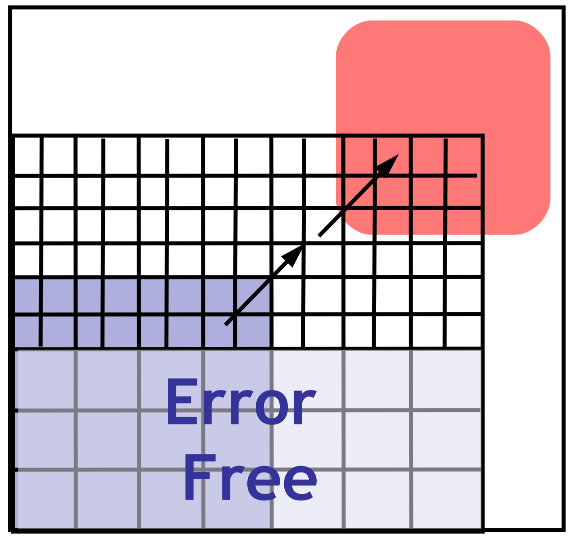
#abstract states = $2^{\#predicates}$

Exponential Thm. Prover queries

Solution

Build abstraction **during** search

Solution2: Don’t Refine Error-Free Regions



Problem

#abstract states = $2^{\#\text{predicates}}$

Exponential Thm. Prover queries

Solution

Don’t refine error-free regions

Sanskrit Epics

- The Ramayana (रामायणम्) consists of over 20,000 Sanskrit verses speaking of virtue, relationships, life and culture. It is a significant text in the Hindu tradition with a large influence on classical poets. *This character* is associated with sacrifice, love and purity. She chooses her husband in a heroic contest from among many others and follows him into exile in the forest.

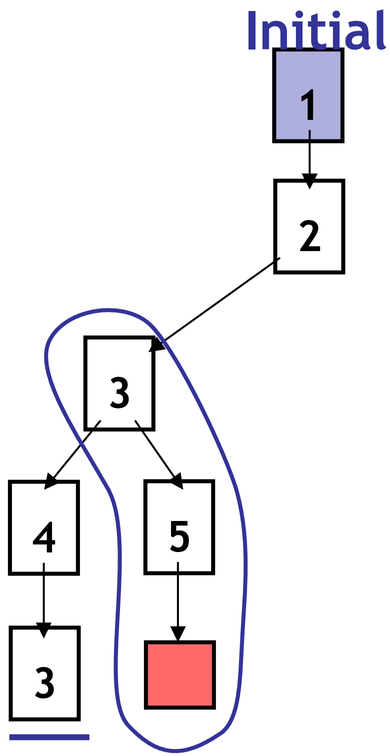
Q: Books (704 / 842)

- In T.S. Eliot's 1939 **Old Possum's Book Of Pratical Cats**, this *"mystery cat is called the hidden paw / for he's a master criminal who can defy the law."*

Q: Computer Science

- This American Turing award winner is sometimes called the “father” of analysis of algorithms, and is known for popularizing asymptotic notation, creating TeX, and co-developing a popular a string search algorithm. His most famous work is *The Art of Computer Programming*.

Key Idea: Reachability Tree



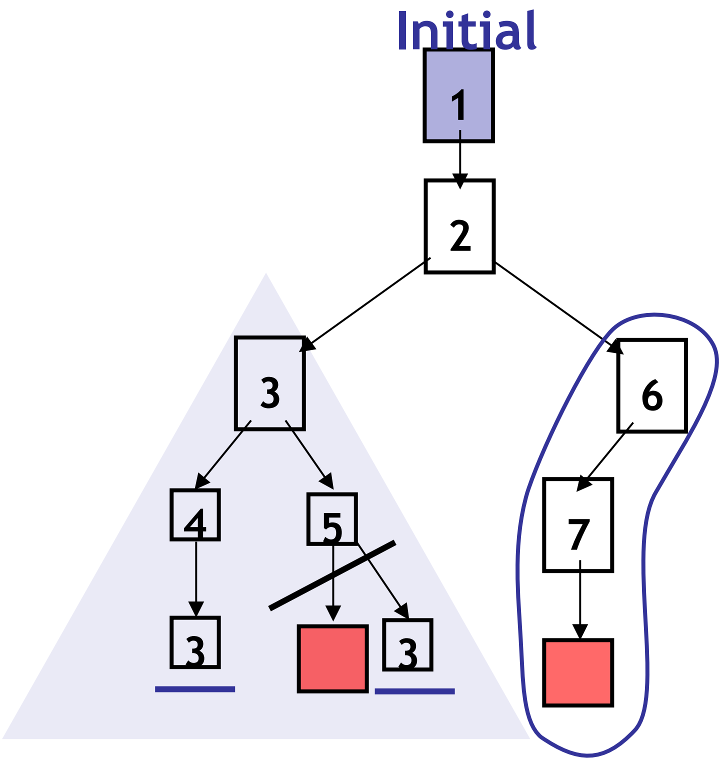
Unroll Abstraction

1. Pick tree-node **(=abs. state)**
2. Add children **(=abs. successors)**
3. On **re-visiting** abs. state, **cut-off**

Find min infeasible suffix

- Learn new predicates
- Rebuild subtree with new preds.

Key Idea: Reachability Tree



Error Free

Unroll Abstraction

1. Pick tree-node **(=abs. state)**
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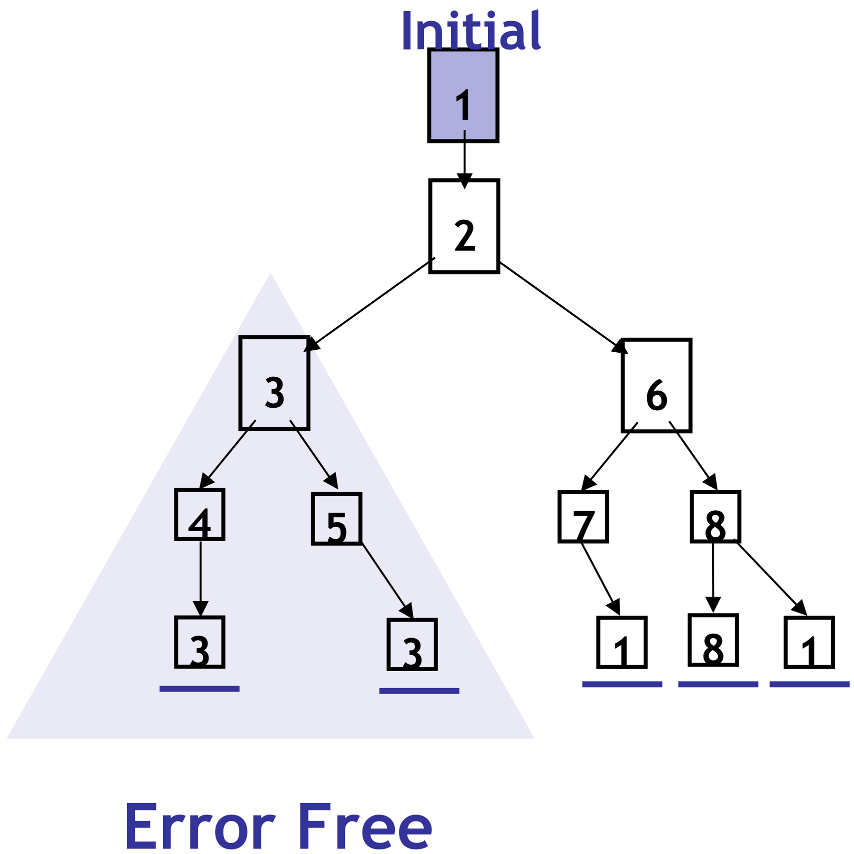
Key Idea: Reachability Tree



Unroll

1. Pick tree-node (=abs. state)
2. Add children (=abs. successors)
3. On re-visiting abs. state, cut-off

Find min spurious suffix

- Learn new predicates
- Rebuild subtree with new preds.

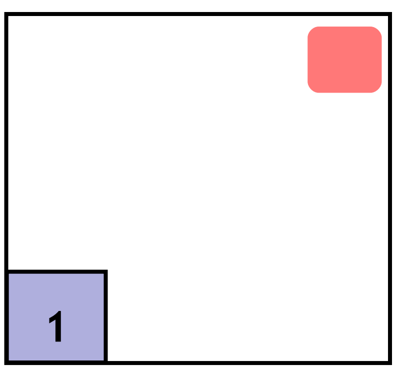
SAFE

S1: Only Abstract Reachable States

S2: Don't refine error-free regions

Build-and-Search

```
Example ( ) {
1: do{
       lock();
       old = new;
       q = q->next;
2:     if (q != NULL){
3:        q->data = new;
          unlock();
          new ++;
       }
4:}while(new != old);
5: unlock ();
}
```



Predicates: *LOCK*

Reachability Tree

Build-and-Search

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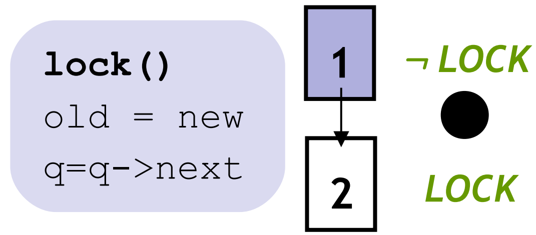

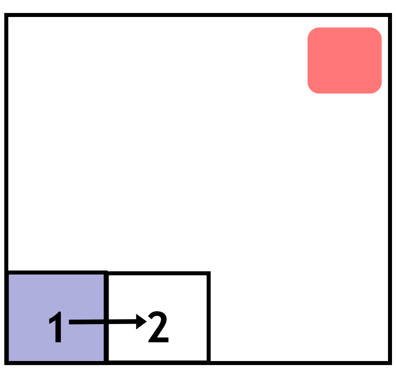

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Reachability Tree

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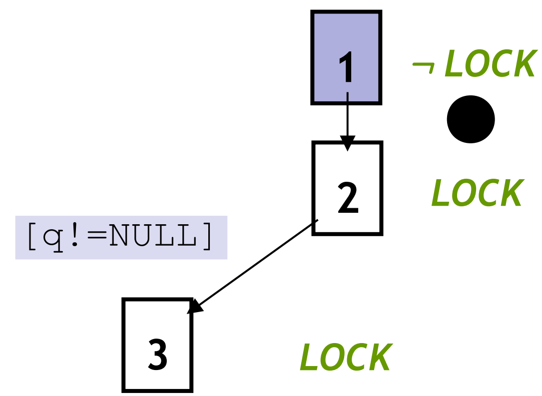

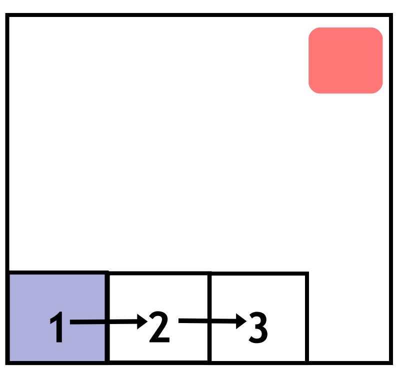

Predicates: *LOCK*

Reachability Tree

Build-and-Search

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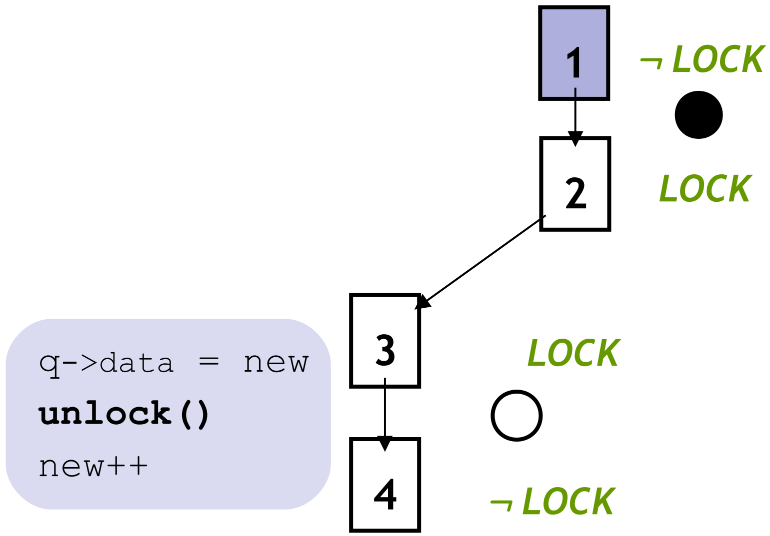

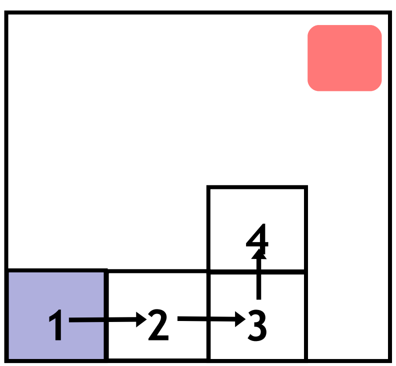

Predicates: *LOCK*

Reachability Tree

Build-and-Search

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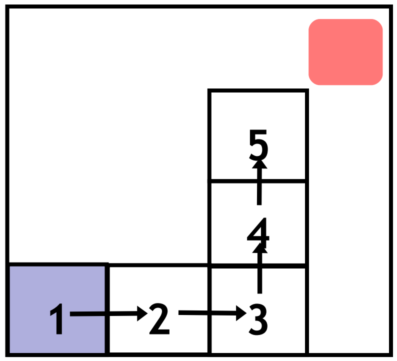
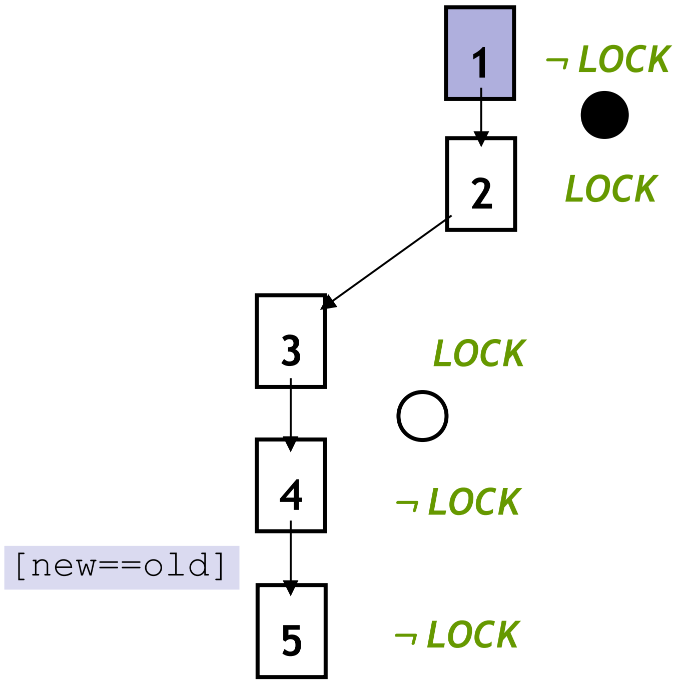


Predicates: *LOCK*



Reachability Tree

Build-and-Search

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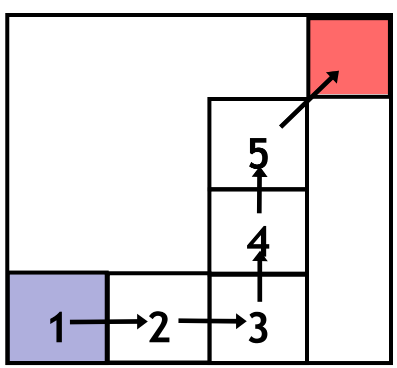
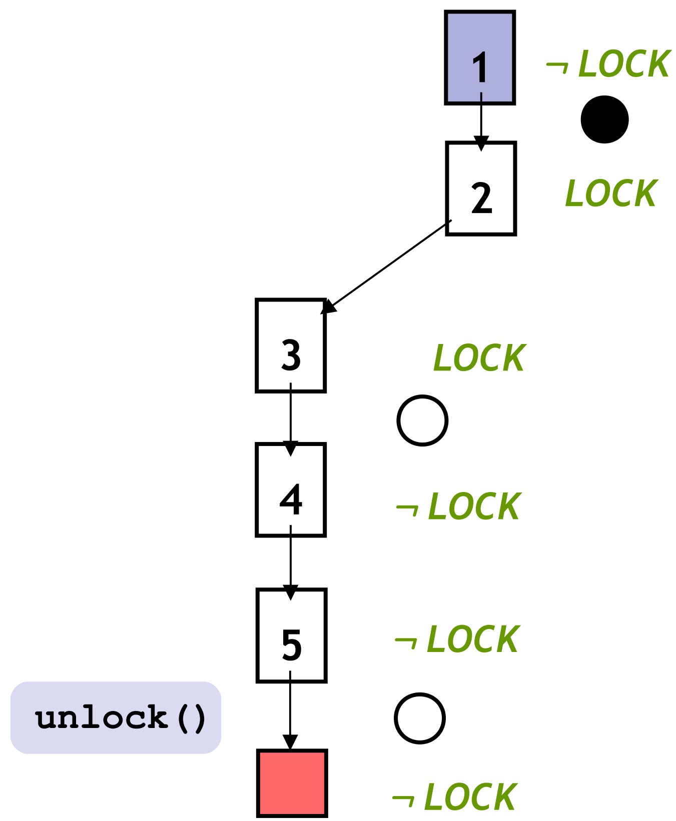


Predicates: *LOCK*



Reachability Tree

Analyze Counterexample

```
Example ( ) {
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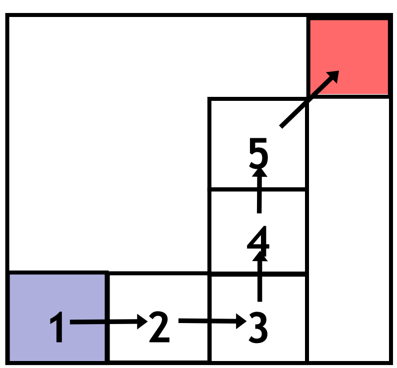
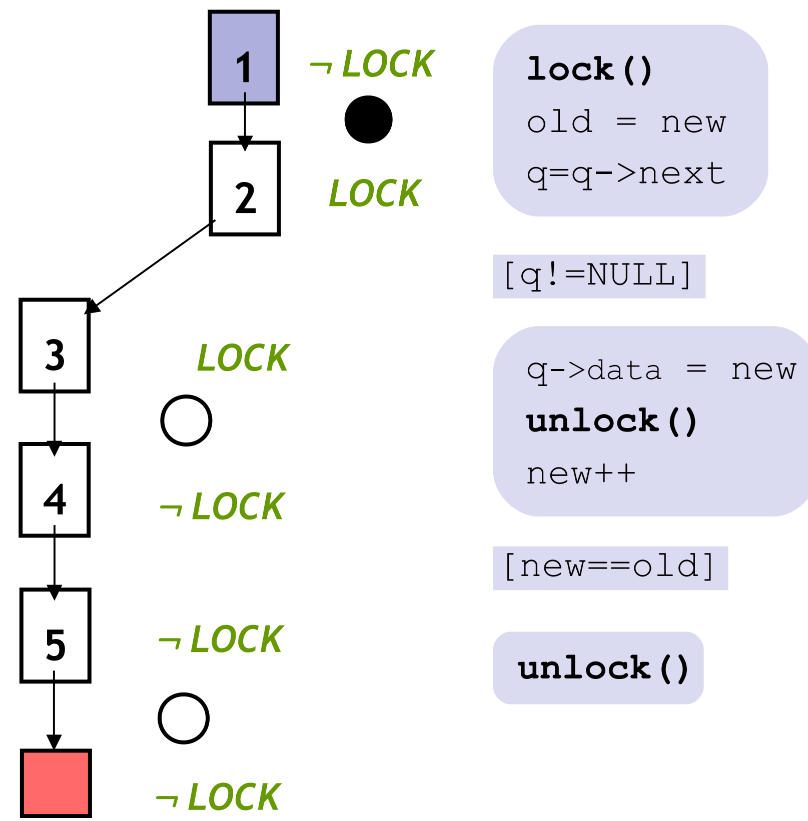


Predicates: *LOCK*



Reachability Tree

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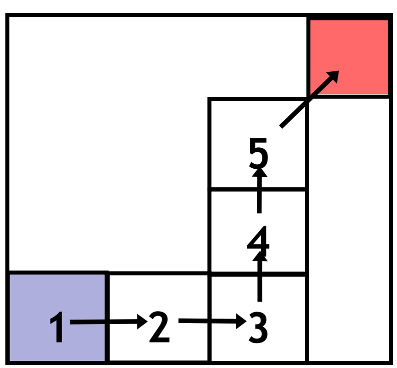
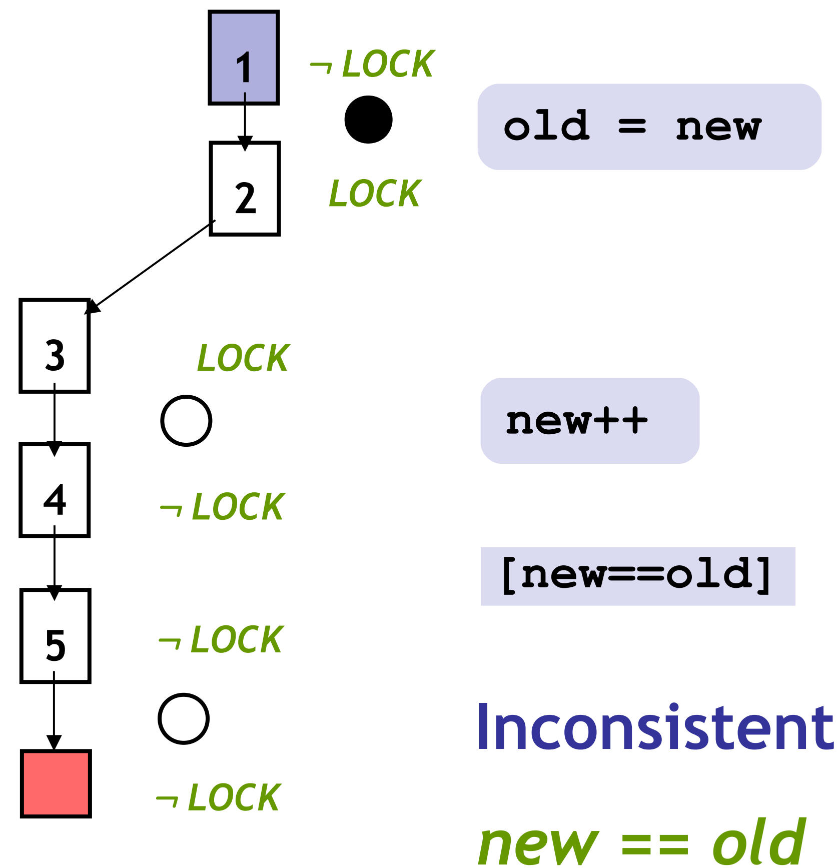


Predicates: *LOCK*



Reachability Tree

Repeat Build-and-Search

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Example ( ) {
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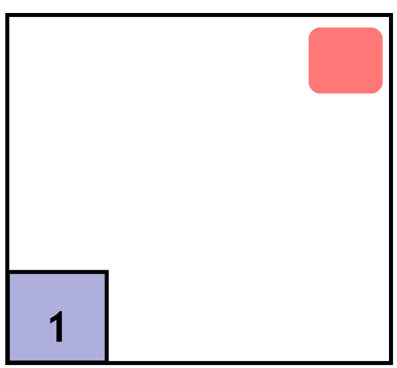

Predicates: *LOCK, new==old*

Reachability Tree

Repeat Build-and-Search

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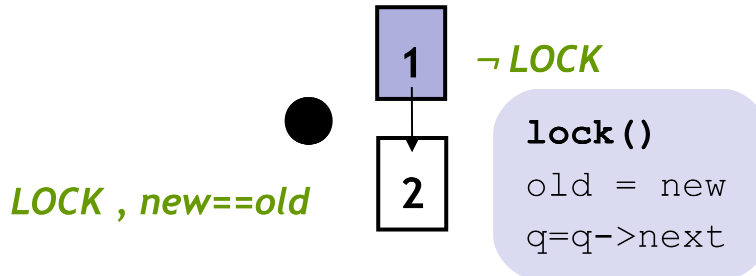

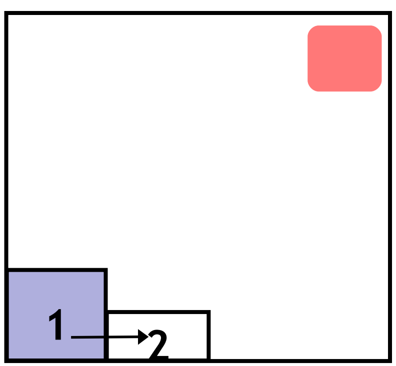

Predicates: *LOCK, new==old*

Reachability Tree

Repeat Build-and-Search

```
Example ( ) {
1: do{
       lock();
       old = new;
       q = q->next;
2:     if (q != NULL){
3:         q->data = new;
           unlock();
           new ++;
       }
4:}while(new != old);
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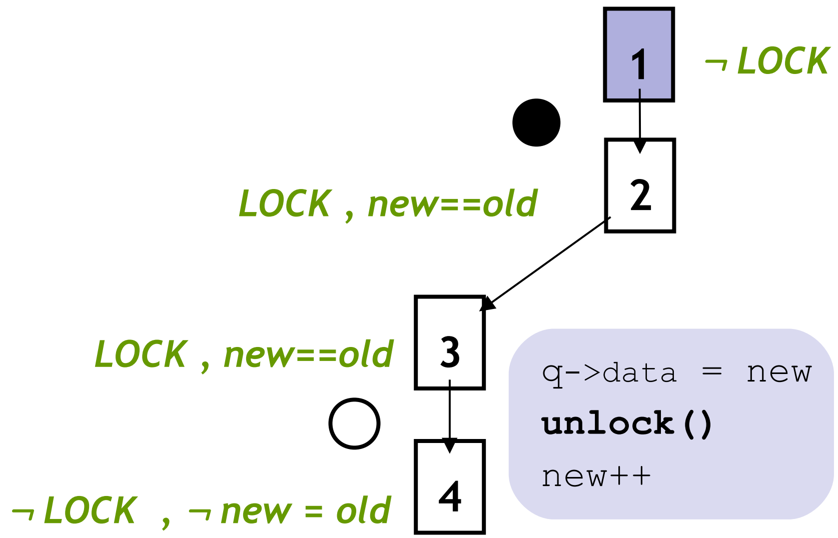

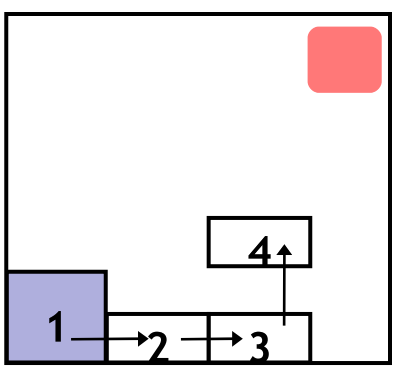

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Reachability Tree

Repeat Build-and-Search

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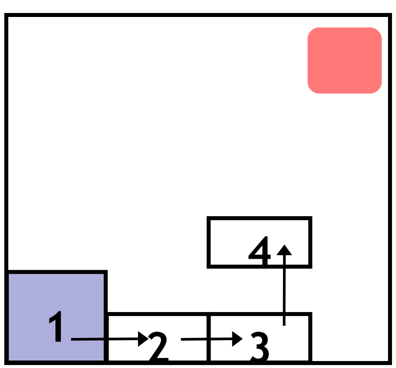

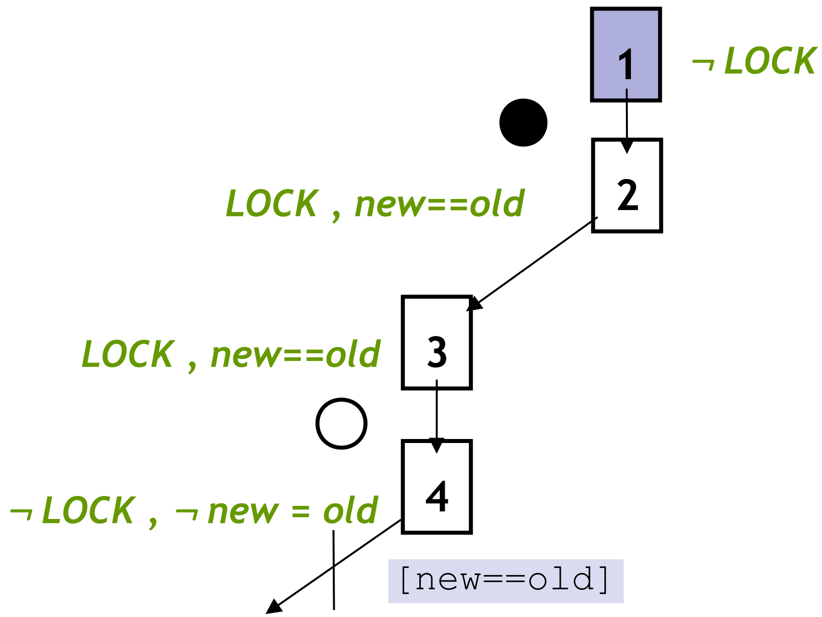

Predicates: *LOCK, new==old*

Reachability Tree

Repeat Build-and-Search

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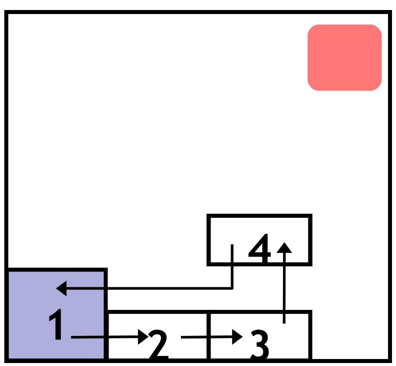

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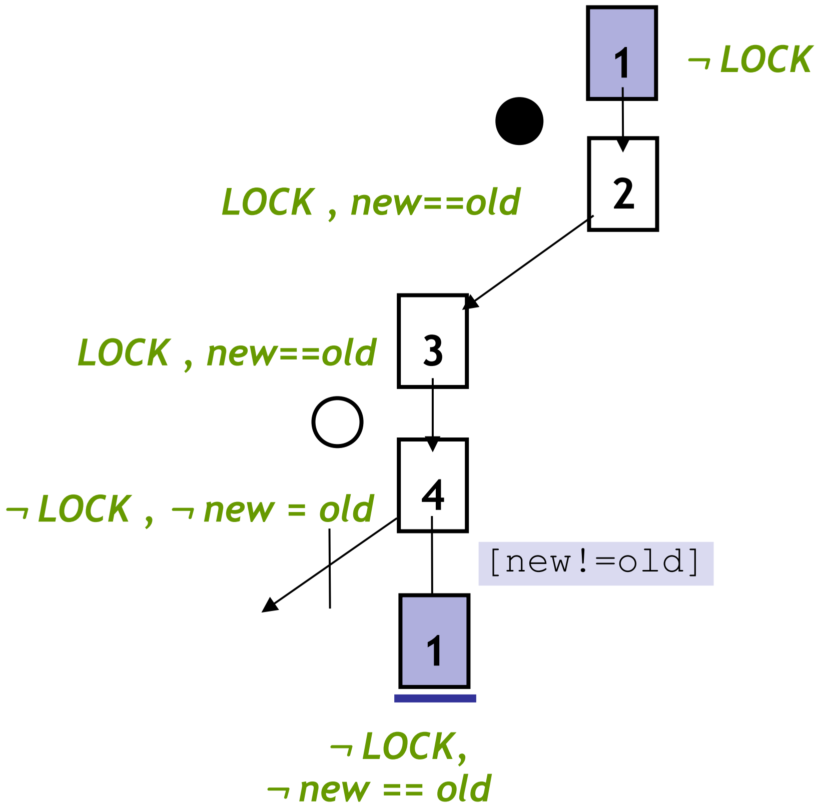

Reachability Tree

Repeat Build-and-Search

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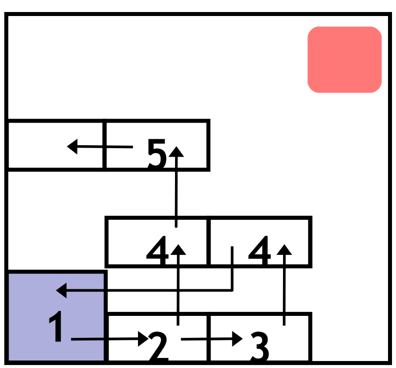
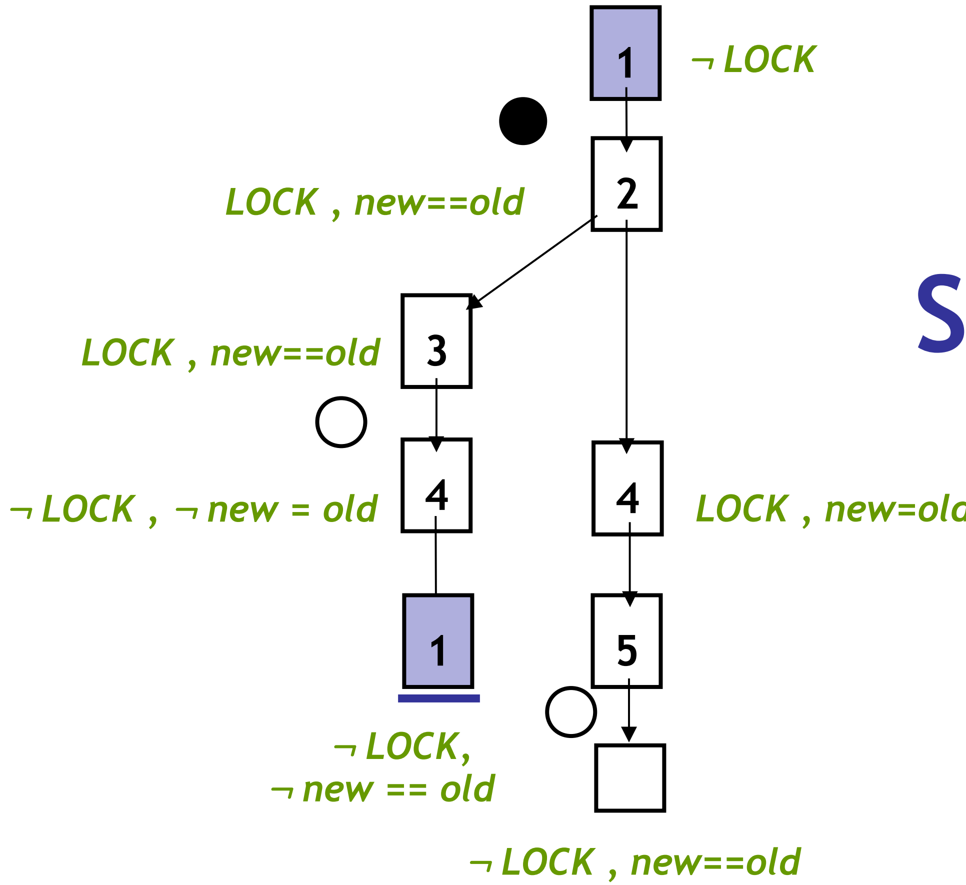


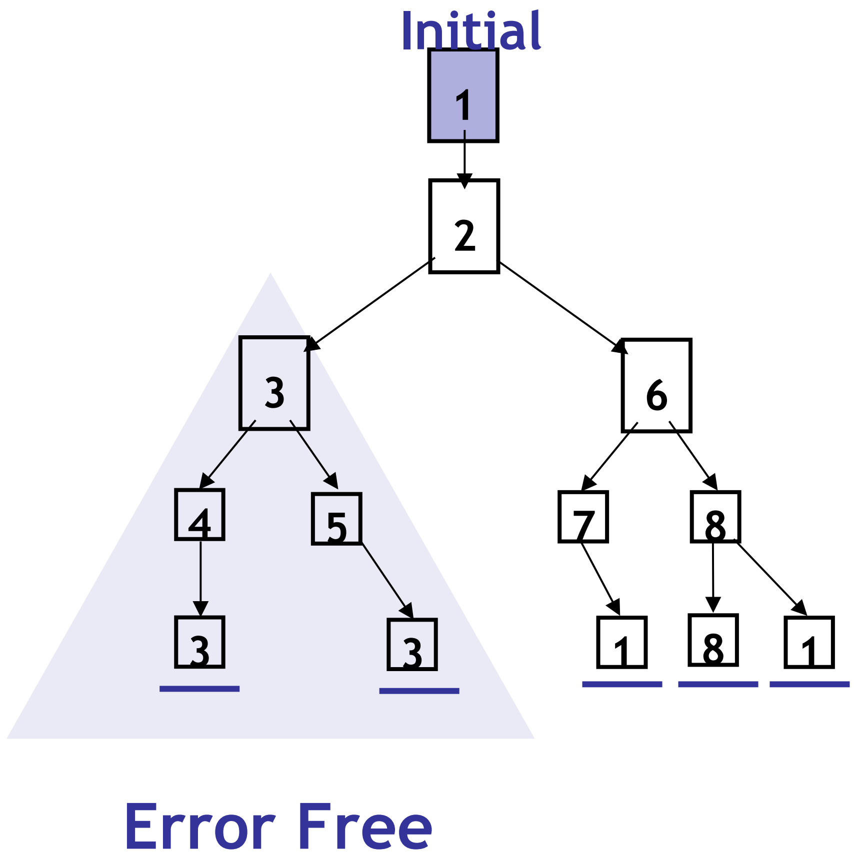
Predicates: *LOCK, new==old*



SAFE

Reachability Tree

Key Idea: Reachability Tree



Unroll

1. Pick tree-node (=abs. state)
2. Add children (=abs. successors)
3. On re-visiting abs. state, cut-off

Find min spurious suffix

- Learn new predicates
- Rebuild subtree with new preds.

SAFE

S1: Only Abstract Reachable States

S2: Don't refine error-free regions

Two handwaves

```
Example ( ) {
1: do{
     lock();
     old = new;
     q = q->next;
2:   if (q != NULL){
3:     q->data = new;
       unlock();
       new ++;
     }
4:}while(new != old);
5: unlock ();
}
```


Predicates: *LOCK, new==old*

Reachability Tree

Two handwaves

```
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```
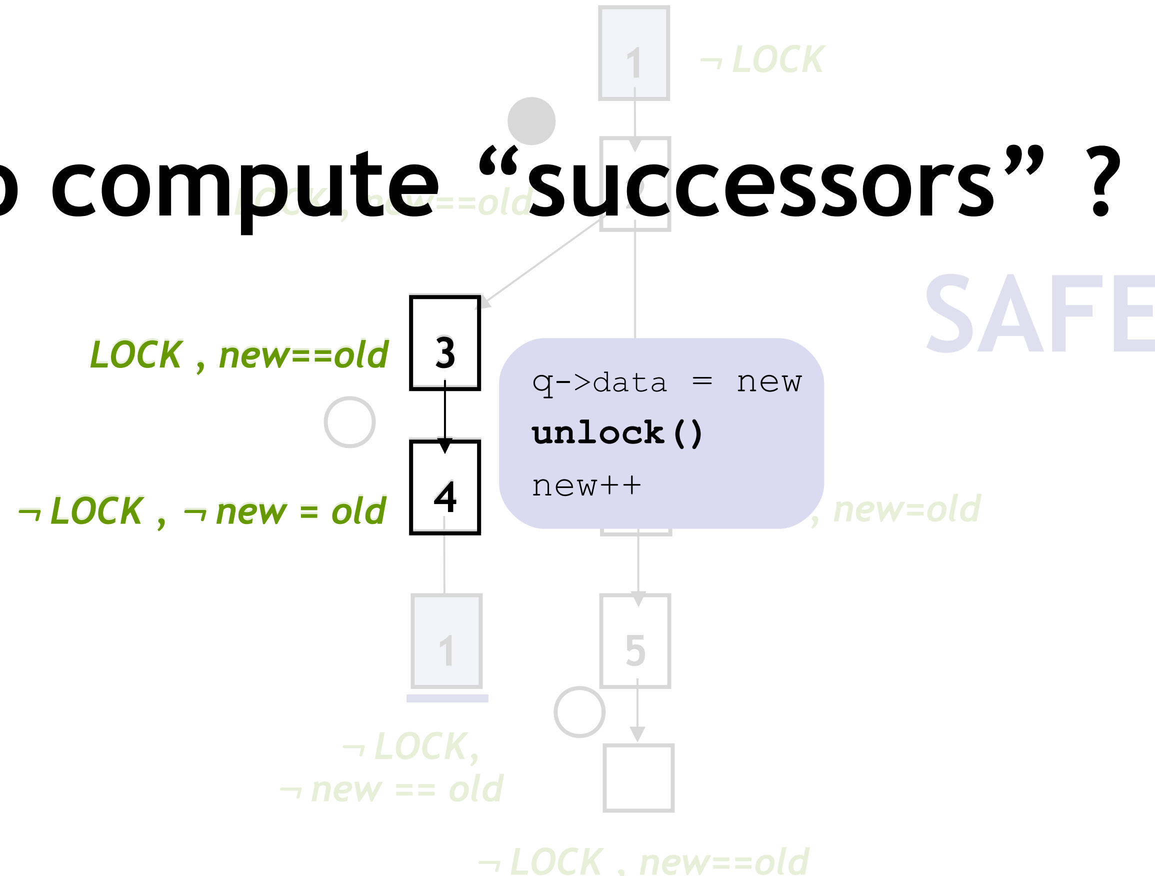

Q. How to compute "successors" ?



Reachability Tree

Predicates: LOCK, new==old

Two handwaves

Q. How to compute "successors" ?

Q. How to find predicates ?

Refinement

Predicates: *LOCK, new==old*

Two handwaves

```
Example ( ) {
1: do{
      lock();
      old = new;
      q = q->next;
2:    if (q != NULL){
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         unlock();
         new ++;
      }
4:}while(new != old);
5: unlock ();
}
```

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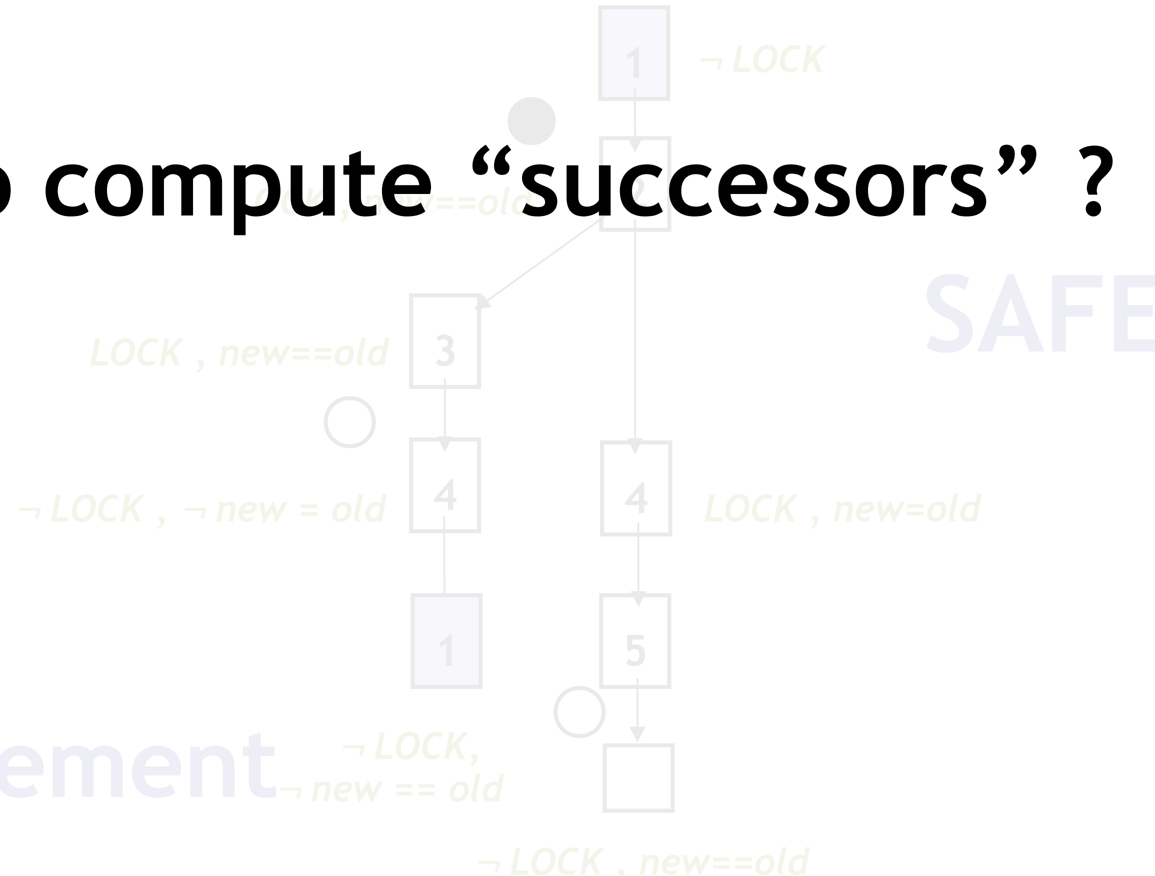


Refinement

Predicates: LOCK, new==old

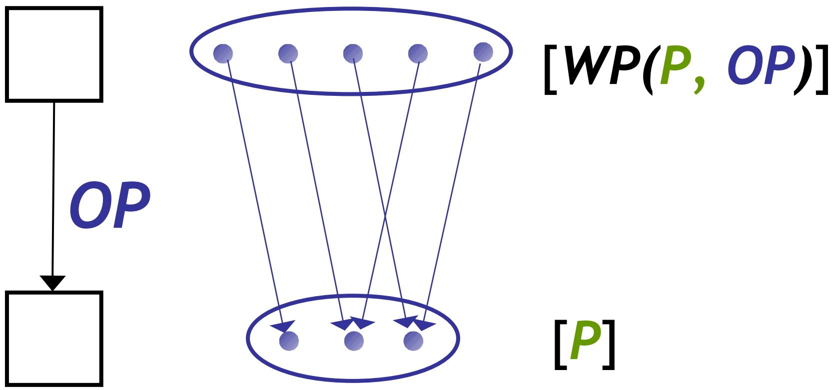
Weakest Preconditions

WP(P,OP)

Weakest formula *P'* s.t.

if *P'* is true <u>before</u> *OP*

then *P* is true <u>after</u> *OP*



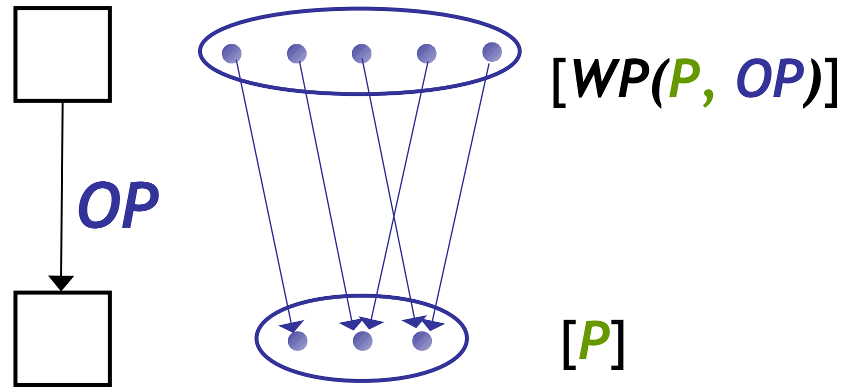
Weakest Preconditions

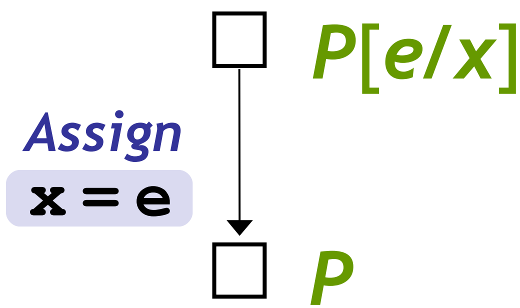
***WP*(*P*,*OP*)**

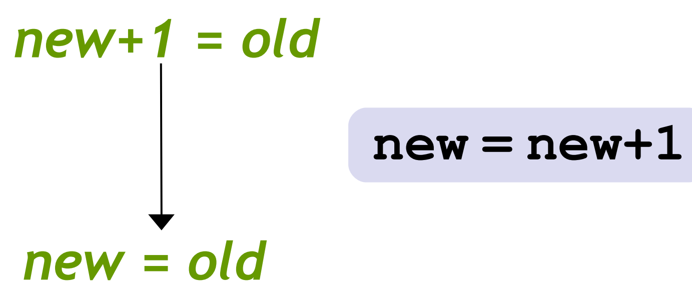
Weakest formula *P'* s.t.

if *P'* is true <u>before</u> *OP*

then *P* is true <u>after</u> *OP*







How to compute successor ?

```
Example ( ) {
1: do{
     lock();
     old = new;
     q = q->next;
2:   if (q != NULL){
3:     q->data = new;
       unlock();
       new ++;
     }
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}
```

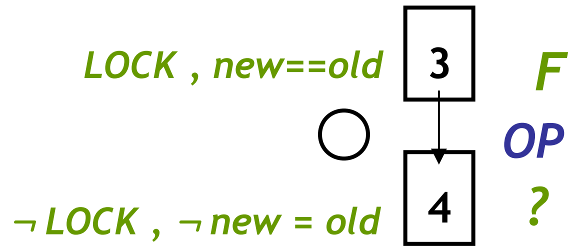

For each *p*

- Check if ***p*** is true (or false) after ***OP***

Q: When is ***p*** true <u>after</u> ***OP*** ?

- If ***WP(p, OP)*** is true <u>before</u> ***OP*** !
- We know ***F*** is true <u>before</u> ***OP***
- Thm. Pvr. Query: $F \Rightarrow WP(p, OP)$

Predicates: *LOCK, new==old*

How to compute successor ?

```
Example ( ) {
1: do{
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}7
```

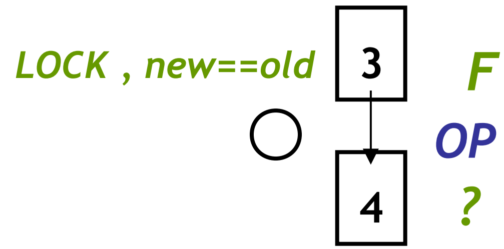

For each *p*

- Check if *p* is true (or false) after ***OP***

Q: When is *p* false <u>after</u> ***OP*** ?

- If ***WP(¬ p, OP)*** is true <u>before</u> ***OP*** !
- We know *F* is true <u>before</u> ***OP***
- Thm. Pvr. Query: $F \Rightarrow WP(\neg p, OP)$

Predicates: *LOCK, new==old*

How to compute successor ?

```
Example ( ) {
1: do{
      lock();
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2:    if (q != NULL){
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         unlock();
         new ++;
      }
4:}while(new != old);
5: unlock ();
}
```

LOCK , new==old **3** *F*

OP

¬ LOCK , ¬ new = old **4** *?*

For each *p*

- Check if *p* is true (or false) after *OP*

Q: When is *p* false <u>after</u> *OP* ?

- If *WP(¬ p, OP)* is true <u>before</u> *OP* !
- We know *F* is true <u>before</u> *OP*
- Thm. Pvr. Query: $F \Rightarrow WP(\neg p, OP)$

Predicate: *new==old*

True ? $(LOCK\ ,\ new==old) \Rightarrow (new + 1 = old)$ ***NO***

False ? $(LOCK\ ,\ new==old) \Rightarrow (new + 1 \neq old)$ ***YES***

Advanced SLAM/BLAST

Too Many Predicates

- Use Predicates Locally

Counter-Examples

- Craig Interpolants

Procedures

- Summaries

Concurrency

- Thread-Context Reasoning

SLAM Summary

1) Instrument Program With Safety Policy
2) Predicates = { }
3) Abstract Program With Predicates
   – Use Weakest Preconditions and Theorem Prover Calls
4) Model-Check Resulting Boolean Program
   – Use Symbolic Model Checking
5) Error State Not Reachable?
   – Original Program Has No Errors: Done!
6) Check Counterexample Feasibility
   • Use Symbolic Execution
7) Counterexample Is Feasible?
   – Real Bug: Done!
8) Counterexample Is Not Feasible?
   1) Find New Predicates (Refine Abstraction)
   2) Goto Line 3

Optional: SLAM Weakness

```
1: F() {
2:   int x=0;
3:   lock();
4:   do x++;
5:   while (x ≠ 88);
6:   if (x < 77)
7:       lock();
8: }
```

- Preds = {}, Path = 234567
- [$x=0$, $\neg x+1 \neq 88$, $x+1<77$]
- Preds = {$x=0$}, Path = 234567
- [$x=0$, $\neg x+1 \neq 88$, $x+1<77$]
- Preds = {$x=0$, $x+1=88$}
- Path = 23454567
- [$x=0$, $\neg x+2 \neq 88$, $x+2<77$]
- Preds = {$x=0$,$x+1=88$,$x+2=88$}
- Path = 2345454567
- …
- Result: the predicates "count" the loop iterations

Homework

- Read Hoare paper
- Read Spolsky article

- Read Winskel Chapter 2