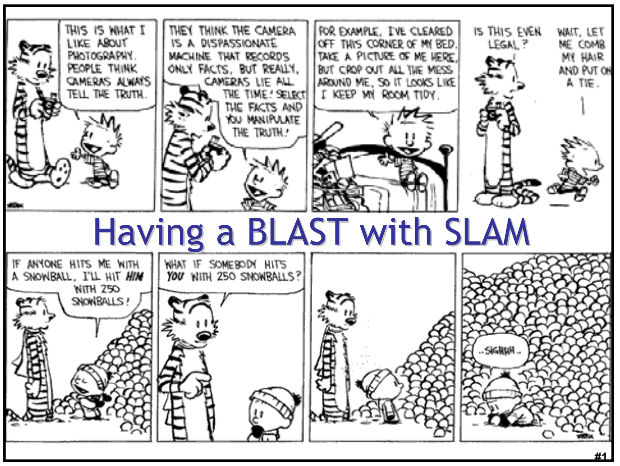


Having a BLAST with SLAM

#1

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

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

#2

Combining Strengths

Theorem Proving

- Need loop invariants
(will find automatically)
+ Behaviors encoded in logic
(used to refine abstraction)
+ Theorem provers
(used to compute successors, refine abstraction)

Program Analysis

- Imprecise
(will be precise)
+ Abstraction
(will shrink the state space we must explore)

SLAM

Model Checking

- Finite-state model, state explosion
(will find small good model)
+ State Space Exploration
(used to get a path sensitive analysis)
+ Counterexamples
(used to find relevant facts, refine abstraction)

#3

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

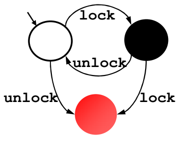
#4

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.

#5

Property 1: Double Locking

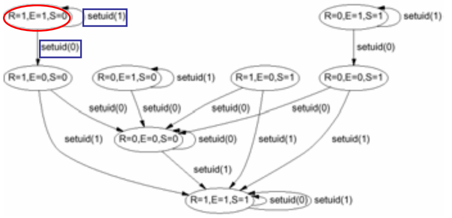


*"An attempt to re-acquire an acquired lock or release a released lock will cause a **deadlock**."*

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

#6

Property 2: Drop Root Privilege

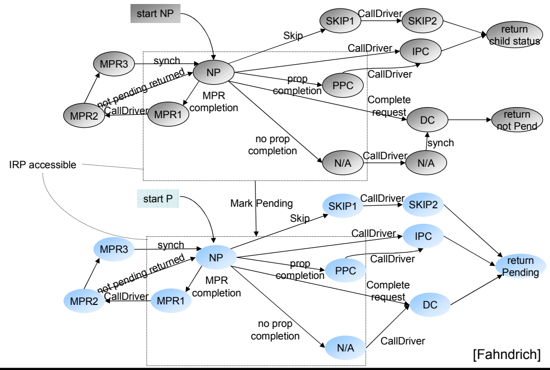


[Chen-Dean-Wagner '02]

"User applications must not run with root privilege"

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

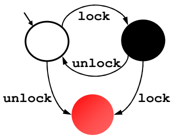
Property 3 : IRP Handler



[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 name
 Program q = incorporate_spec(p,s);               // slic
 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;
}
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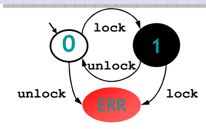
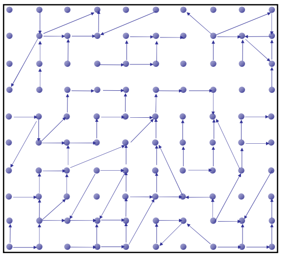
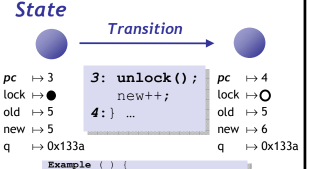



```
Example ( ) {
1: do{
       if L=1 goto ERR;
       else L=1;
       old = new;
       q = q->next;
2:     if (q != NULL){
3:         q->data = new;
           if L=0 goto ERR;
           else L=0;
           new ++;
       }
4: } while(new != old);
5:   if L=0 goto ERR;
     else L=0;
     return;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

Original program violates spec iff new program reaches ERR

Program As Labeled Transition System



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     return; }
```
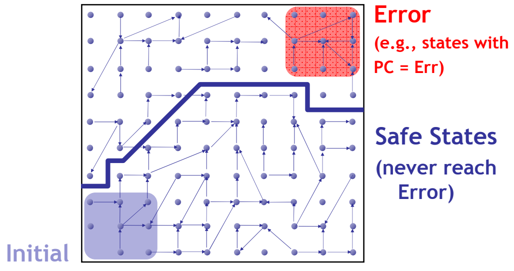

The Safety Verification Problem



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

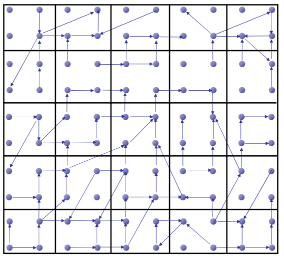
Problem: **Infinite** state graph (old=1, old=2, old=…)

Solution : **Set** of states ≃ logical **formula**

Representing [Sets of States] as *Formulas*

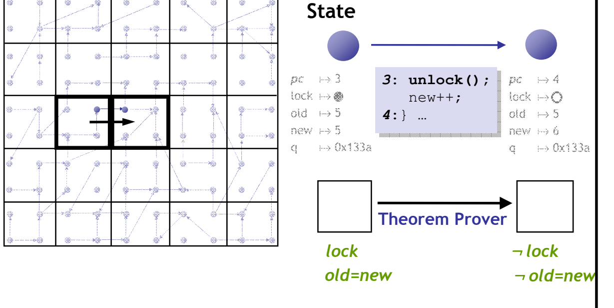
$[F]$ states satisfying F $\{s \mid s \models F\}$	F FO fmla over prog. vars
$[F_1] \cap [F_2]$	$F_1 \wedge F_2$
$[F_1] \cup [F_2]$	$F_1 \vee F_2$
$\overline{[F]}$	$\neg F$
$[F_1] \subseteq [F_2]$	$F_1 \Rightarrow F_2$
	i.e. $F_1 \wedge \neg F_2$ unsatisfiable

Idea 1: Predicate Abstraction

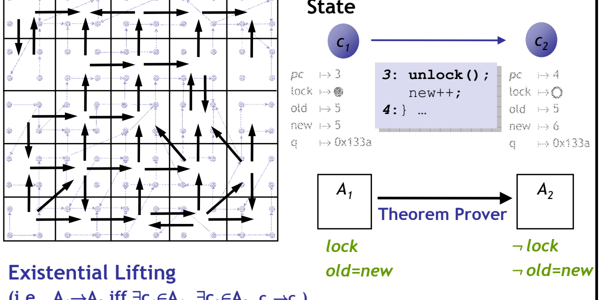


- **Predicates** on program state:
  lock (*i.e., lock=true*)
  old = new
- States satisfying **same** predicates are **equivalent**
  - **Merged** into one **abstract state**
- #abstract states is **finite**
  - Thus model-checking the abstraction will be feasible!

Abstract States and Transitions

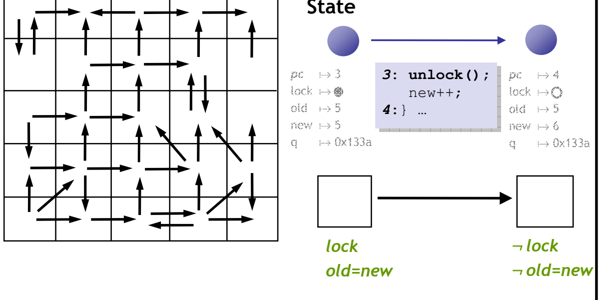


Abstraction

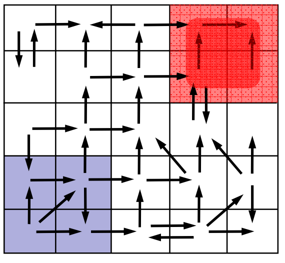


Existential Lifting
(i.e., $A_1 \to A_2$ iff $\exists c_1 \in A_1.\ \exists c_2 \in A_2.\ c_1 \to c_2$)

Abstraction



Analyze Abstraction



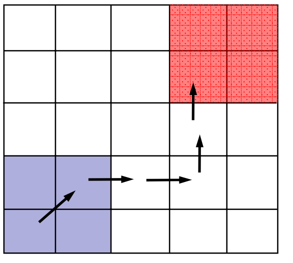
Analyze finite graph

Over Approximate:
Safe ⇒ System Safe

No **false negatives**

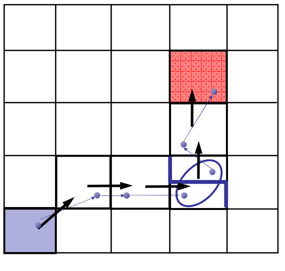
Problem
Spurious **counterexamples**

Idea 2: Counterex.-Guided Refinement



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

Idea 2: Counterex.-Guided Refinement

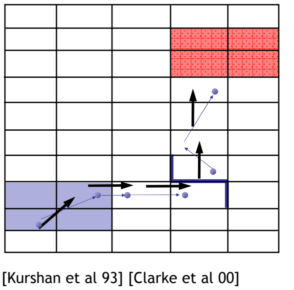


Solution
Use spurious **counterexamples** to **refine** abstraction

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

Imprecision due to **merge**

Iterative Abstraction-Refinement

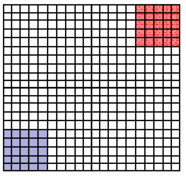


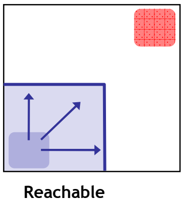
[Kurshan et al 93] [Clarke et al 00]
[Ball-Rajamani 01]

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



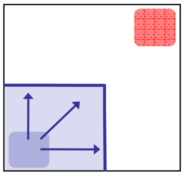


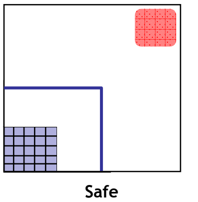
Reachable

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



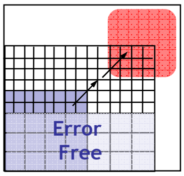


Safe

Problem
#abstract states = $2^{\#predicates}$
Exponential Thm. Prover queries

Solution
Build abstraction **during** search

Solution2: Don’t Refine Error-Free Regions



Problem

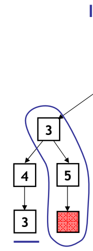
#abstract states = $2^{\#predicates}$

Exponential Thm. Prover queries

Solution

Don’t refine error-free regions

Key Idea: Reachability Tree



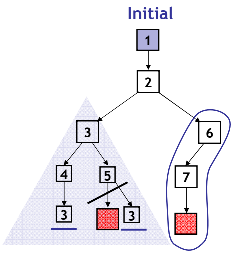
Unroll Abstraction

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



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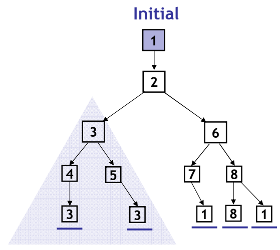

Unroll

1. Pick tree-node (=abs. state)
2. Add children (=abs. successors)
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Find min spurious suffix

- Learn new predicates
- Rebuild subtree with new preds.

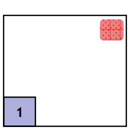
SAFE

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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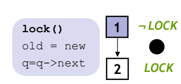

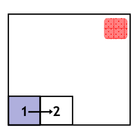

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Reachability Tree

Build-and-Search

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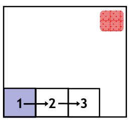

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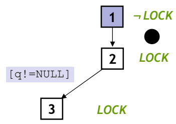

Reachability Tree

Build-and-Search

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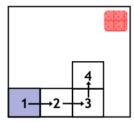

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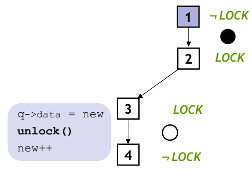

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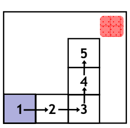

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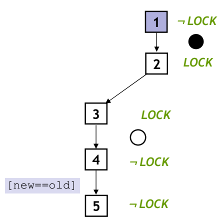

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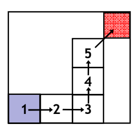

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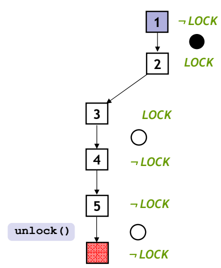

Reachability Tree

Analyze Counterexample

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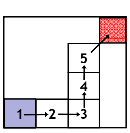

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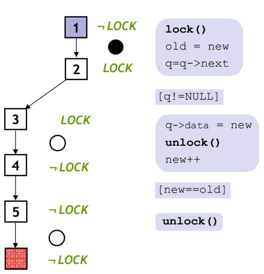

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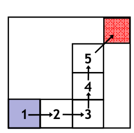
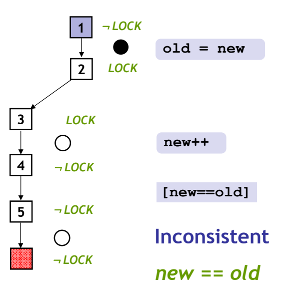


Predicates: *LOCK*



Reachability Tree

Repeat Build-and-Search

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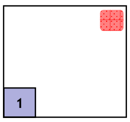

Reachability Tree

Predicates: *LOCK, new==old*

Repeat Build-and-Search

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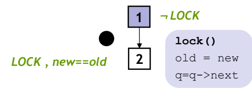

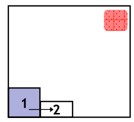

Reachability Tree

Predicates: *LOCK, new==old*

Repeat Build-and-Search

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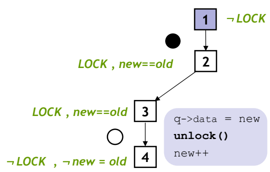

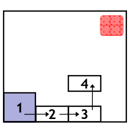

Reachability Tree

Predicates: *LOCK, new==old*

Repeat Build-and-Search

```
Example ( ) {
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     lock();
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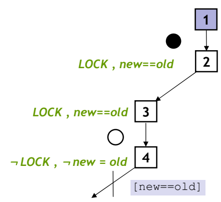

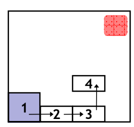

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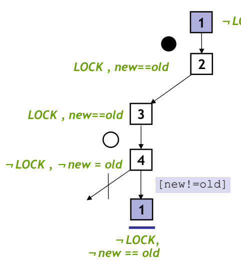

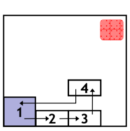

Reachability Tree

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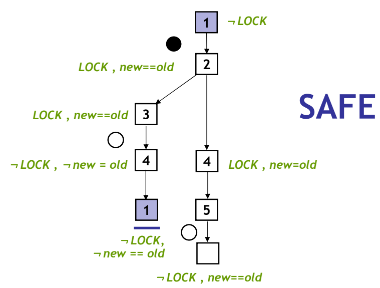
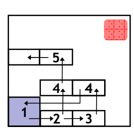
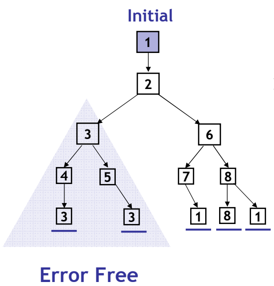




Reachability Tree

Predicates: *LOCK, new==old*

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

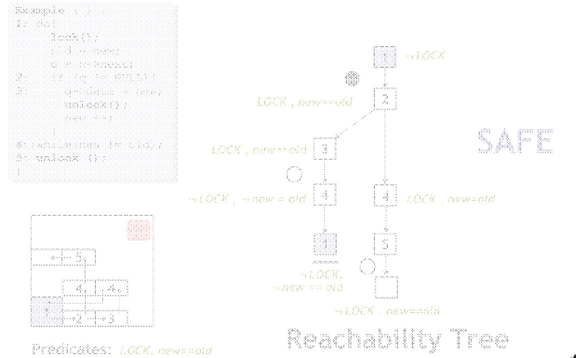
- Learn new predicates
- Rebuild subtree with new preds.

SAFE

S1: Only Abstract Reachable States

S2: Don't refine error-free regions

Two handwaves



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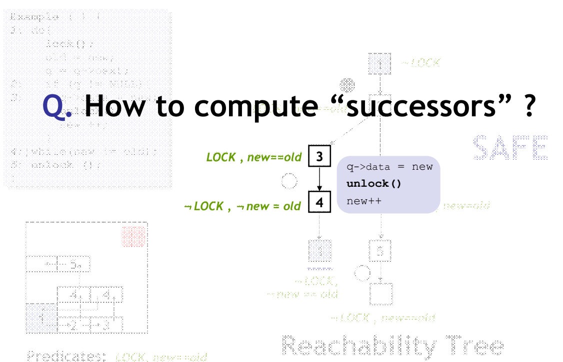
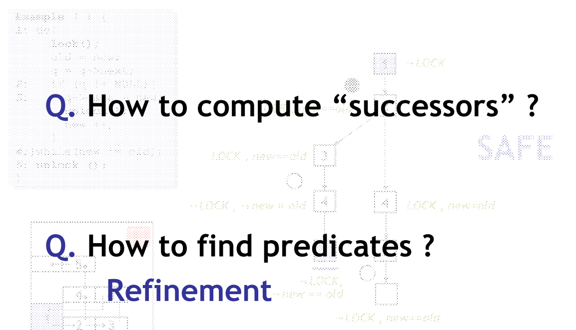


Q. How to compute "successors" ?

Two handwaves



Q. How to compute "successors" ?

Q. How to find predicates ?

Refinement

Predicates: *LOCK, new==old*

Two handwaves

Q. How to compute "successors" ?

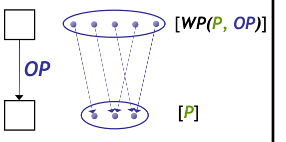
Weakest Preconditions

WP(P,OP)

Weakest formula *P'* s.t.

if *P'* is true before *OP*

then *P* is true after *OP*



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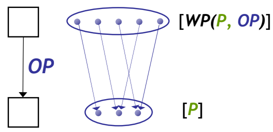

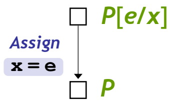

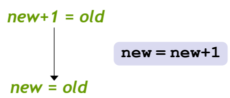

How to compute successor ?

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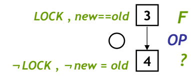
2:    if (q != NULL){
3:       q->data = new;
         unlock();
         new ++;
      }
4:}while(new != old);
5: unlock ();
}
```



For each *p*

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

Q: When is *p* true after *OP* ?

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

Predicates: *LOCK, new==old*

How to compute successor ?

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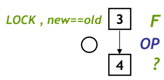
}7
```



For each *p*

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

Q: When is *p* false after *OP* ?

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

Predicates: *LOCK, new==old*

How to compute successor ?

```
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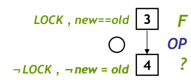

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- We know *F* is true before *OP*
- Thm. Pvr. Query: $F \Rightarrow WP(\neg p, OP)$

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
   1) Use Weakest Preconditions and Theorem Prover Calls
4) Model-Check Resulting Boolean Program
   1) Use Symbolic Model Checking
5) Error State Not Reachable?
   1) Original Program Has No Errors: Done!
6) Check Counterexample Feasibility
   1) Use Symbolic Execution
7) Counterexample Is Feasible?
   1) 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, ¬x+1≠88, x+1<77]
- Preds = {x=0}, Path = 234567
- [x=0, ¬x+1≠88, x+1<77]
- Preds = {x=0, x+1=88}
- Path = 234567
- [x=0, ¬x+2≠88, x+2<77]
- Preds = {x=0,x+1=88,x+2=88}
- Path = 234545467
- …
- Result: the predicates "count" the loop iterations

Homework

- Project Due