Counterexample Guided Abstraction Refinement in Blast

Optional reading: ***Checking Memory Safety with Blast***

17-355/17-665: Program Analysis

Jonathan Aldrich

How would you analyze this?

```
 Example() {
1:   if (*){
7:       do {
              got_lock = 0;
8:            if (*){
9:                lock();
                  got_lock++;
              }
10:           if (got_lock){
11:               unlock();
              }
12:      } while (*)
     }
```

- * means something we can't analyze (user input, random value)
- Line 10: the lock is held if and only if got_lock = 1

How would you analyze this?

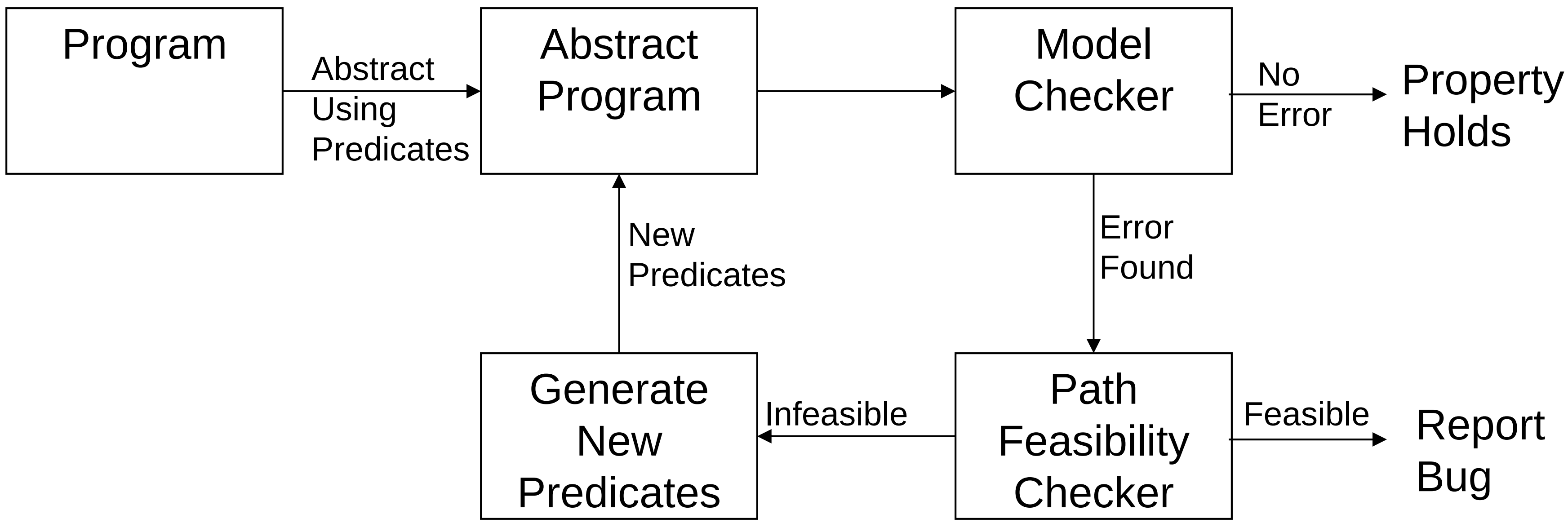
```
2:   do {
            lock();
            old = new;
3:          if (*){
               unlock();
               new++;
            }
5:   } while (new != old);
6:   unlock();
     return;
```

- * means something we can't analyze (user input, random value)
- Line 5: the lock is held if and only if old = new

Motivation

- Dataflow analysis uses fixed abstraction
  - e.g. zero/nonzero, locked/unlocked
  - Model checking version of DFA similar
- Symbolic execution shows need to eliminate infeasible paths
  - E.g. lock/unlock on correlated branches
  - Requires extending abstraction with branch predicates
- It's hard to make symbolic execution sound
  - Infeasible to cover all paths
  - Although we can merge paths with similar analysis info, the information is too detailed to assure finitely many explored paths
- Can we get both soundness and the precision to eliminate infeasible paths?
  - In general: of course not! That's undecidable.
  - But in many situations we can solve it with *abstraction refinement*; it's just that this technique may not always terminate

CEGAR:
Counterexample Guided Abstraction Refinement

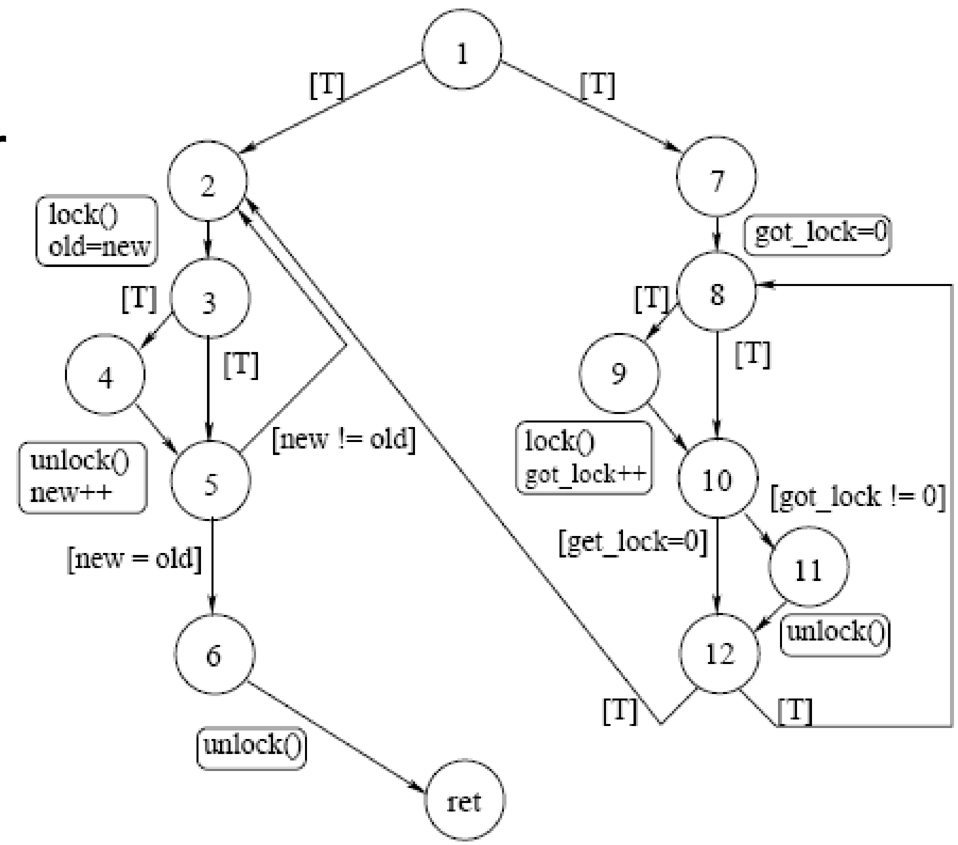


CEGAR:
Counterexample Guided Abstraction Refinement

- Begin with control flow graph abstraction
- Check reachability of error nodes
  - Typically take cross product of dataflow abstraction and CFG
  - However, can encode dataflow abstraction in CFG through error nodes—assert(false)
- If error node is reachable, check if path is feasible
  - Can use weakest preconditions; if you get false, the path is impossible
- For feasible paths, report an error
- For infeasible paths, figure out why
  - e.g. correlation between lock and got_lock
- Add reason for infeasible paths to abstraction and try again!
  - This time the analysis won't consider that path
  - But it might consider other infeasible paths, so you may have to repeat the process multiple times

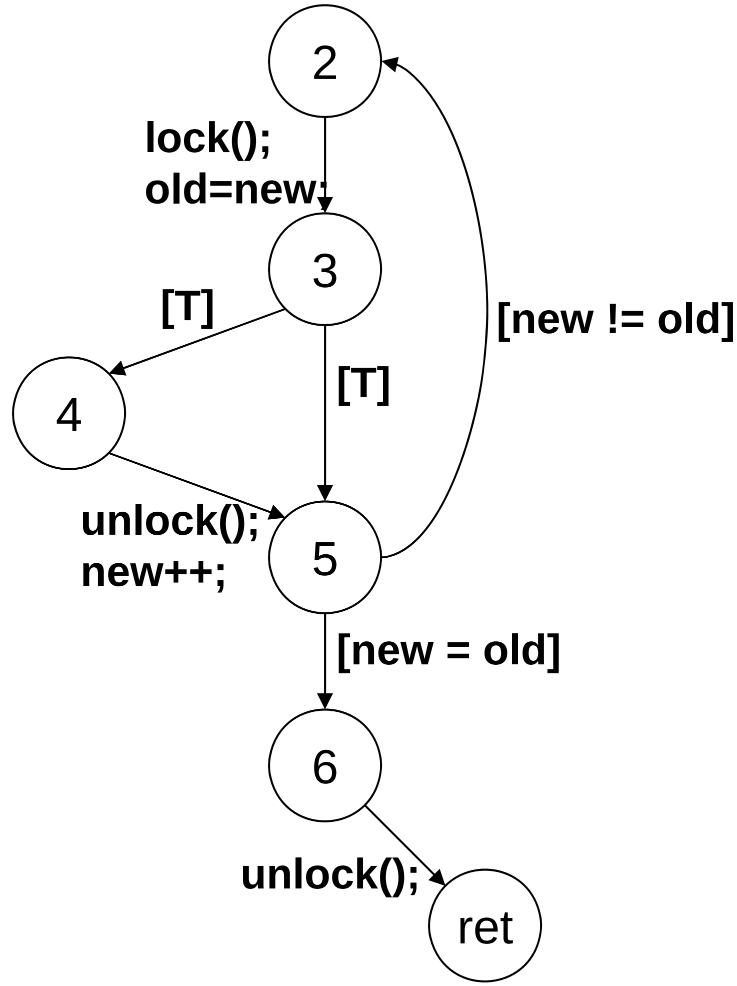
Control Flow Automaton

- One node for each location (before/after a statement)
- Edges
  - Blocks of statements
  - Assume clauses model if and loops
    - some predicate must be true to take the edge



Control Flow Automaton Example

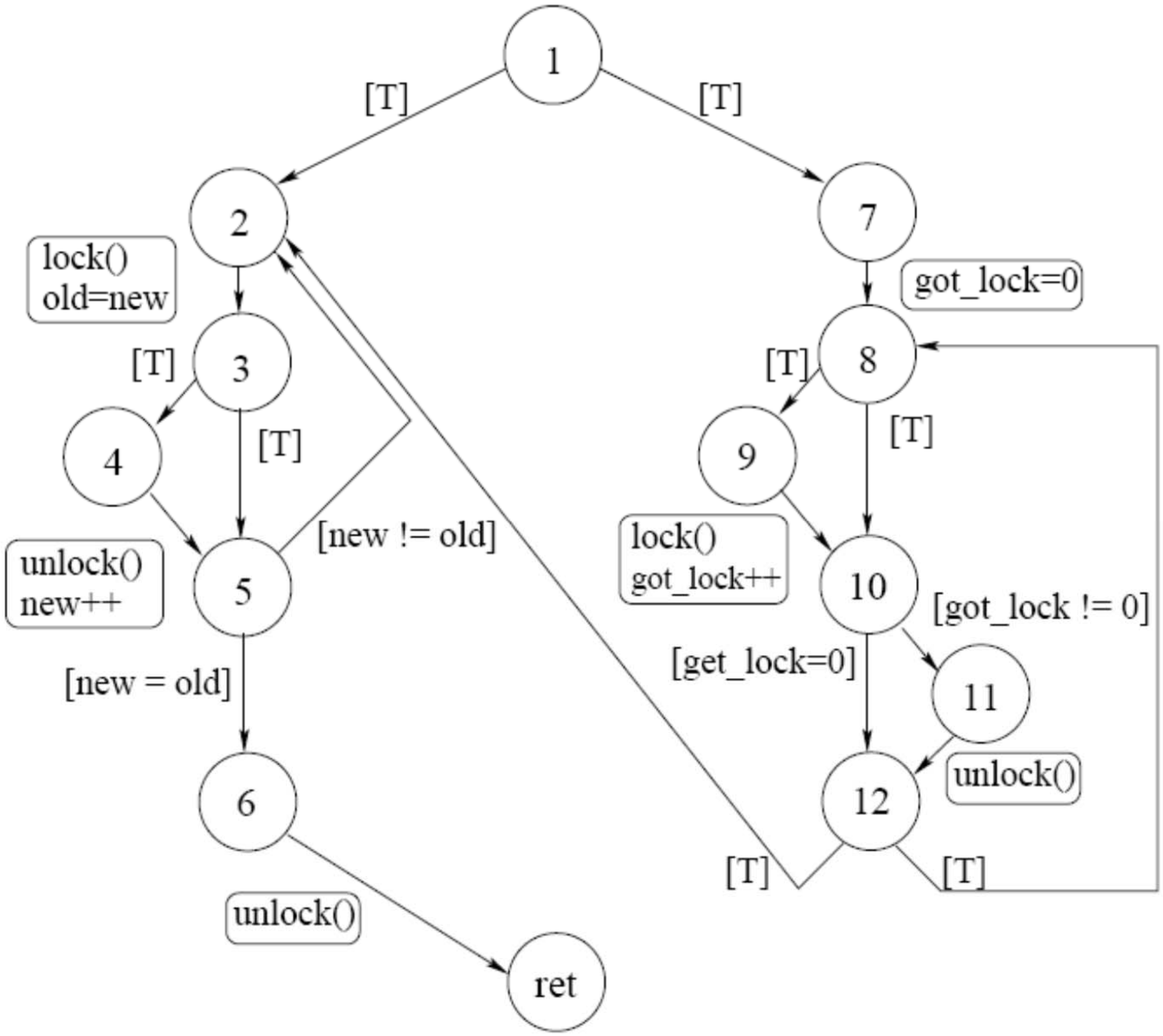
```
2:  do {
          lock();
          old = new;
3:        if (*){
4:            unlock();
              new++;
          }
5:  } while (new != old);
6:  unlock();
    return;
```

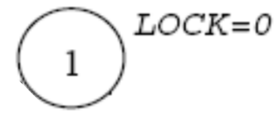


Checking for Reachability

- Generate Abstract Reachability Tree
  - Contains all reachable nodes
  - Annotates each node with state
    - Initially LOCK = 0 or LOCK = 1
    - Cross product of CFA and data flow abstraction
- Algorithm: depth-first search
  - Generate nodes one by one
  - If you come to a node that's already in the tree, stop
    - This state has already been explored through a different control flow path
  - If you come to an error node, stop
    - The error is reachable

Depth First Search Example



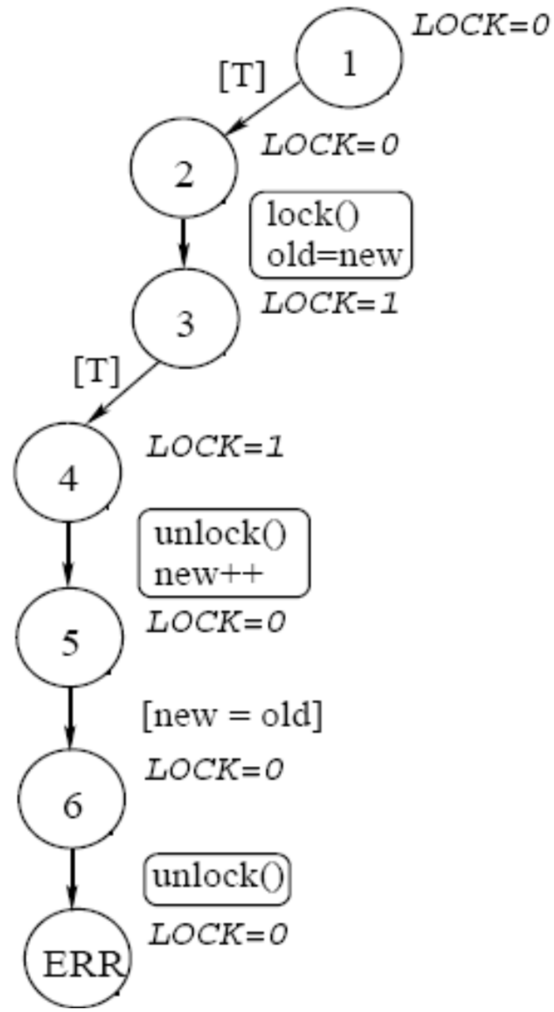


Is the Error Real?

- Use weakest preconditions to find out the weakest precondition that leads to the error
  - If the weakest precondition is false, there is no initial program condition that can lead to the error
  - Therefore the error is spurious
- Blast uses a variant of weakest preconditions
  - creates a new variable for each assignment before using weakest preconditions
  - Instead of substituting on assignment, adds new constraint
  - Helps isolate the reason for the spurious error more effectively

Is the Error Real?

- assume True;
- lock();
- old = new;
- assume True;
- unlock();
- new++;
- assume new==old
- error (lock==0)



Model Locking as Assignment

- assume True;
- lock = 1;
- old = new;
- assume True;
- lock = 0;
- new = new + 1;
- assume new==old
- error (lock==0)

Index the Variables

- assume True;
- lock1 = 1
- old1 = new1;
- assume True;
- lock2 = 0
- new2 = new1 + 1
- assume new2==old1
- error (lock2==0)

Generate Weakest Preconditions

• assume True;	∧ True
• lock1 = 1	∧ lock1==1
• old1 = new1;	∧ old1==new1
• assume True;	∧ True
• lock2 = 0	∧ lock2==0
• new2 = new1 + 1	∧ new2==new1+1
• assume new2==old1	∧ new2==old1
• error (lock2==0)	lock2==0

Contradictory!

Why is the Error Spurious?

- More precisely, what predicate could we track that would eliminate the spurious error message?
- Consider, for each node, the constraints generated before that node (c1) and after that node (c2)
- Find a condition I such that
  - c1 => I
    - I is true at the node
  - I only contains variables mentioned in both c1 and c2
    - I mentions only variables in scope (not old or future copies)
  - I $\wedge$ c2 = false
    - I is enough to show that the rest of the path is infeasible
  - I is guaranteed to exist
    - See Craig Interpolation

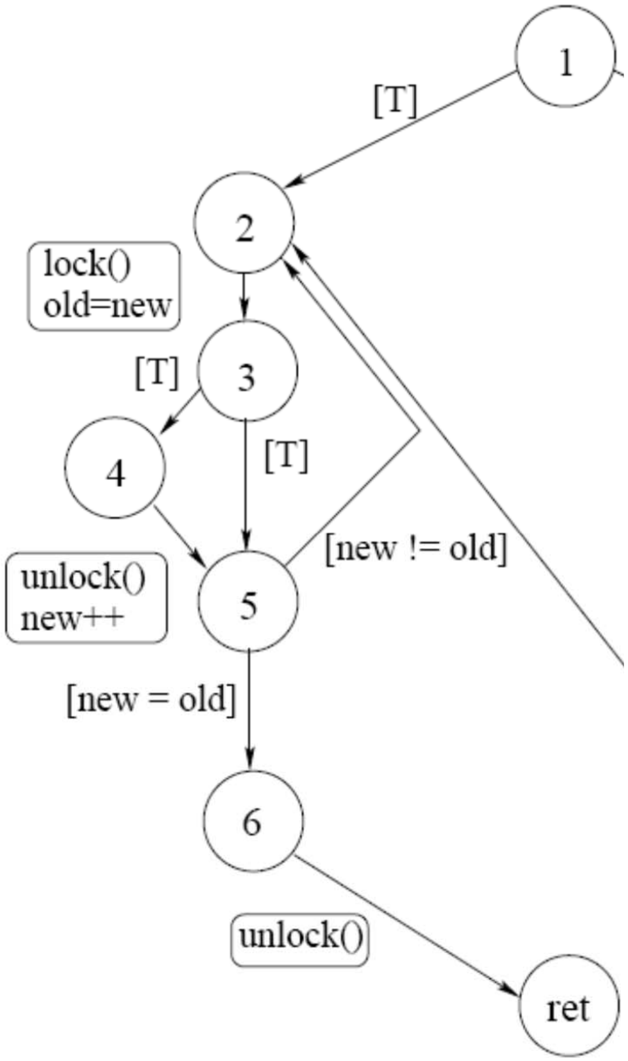
- $\wedge$ True
- $\wedge$ lock1==1
- $\wedge$ old1==new1
- $\wedge$ True
- $\wedge$ lock2==0
- $\wedge$ new2==new1+1
- $\wedge$ new2==old1
- lock2==0

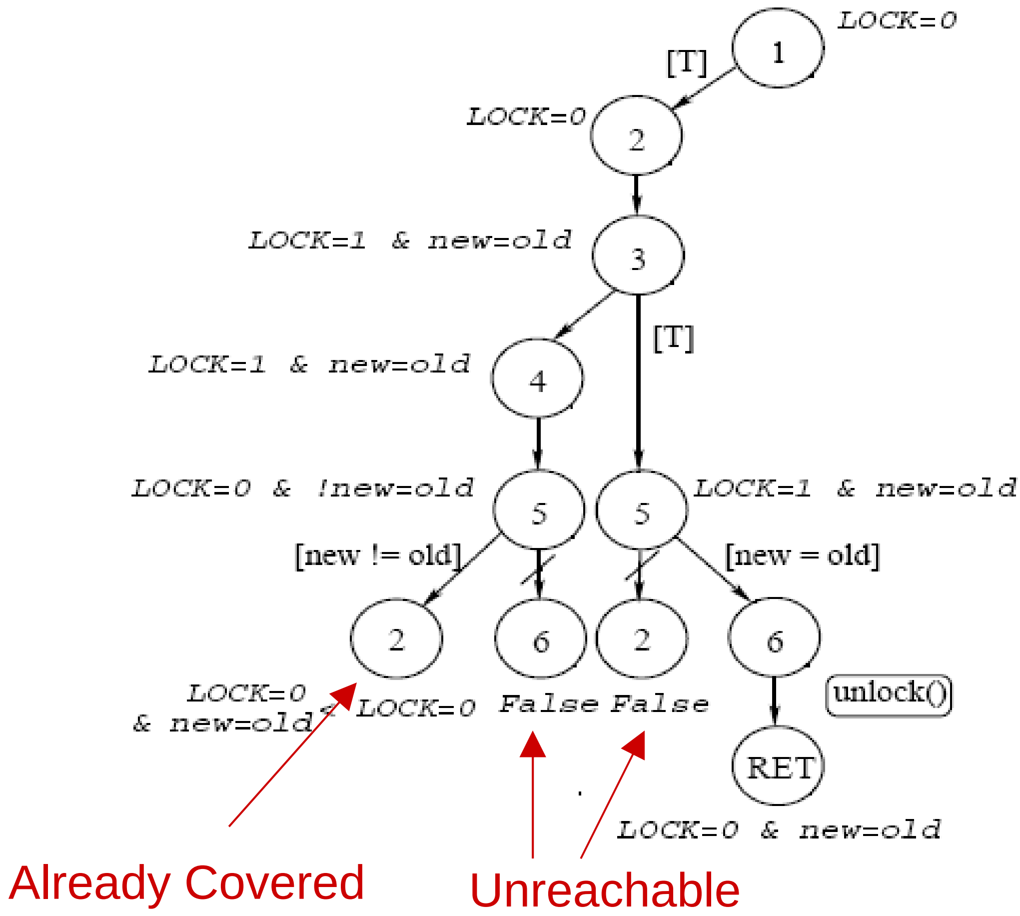
Interpolant: old == new

Reanalyzing the Program

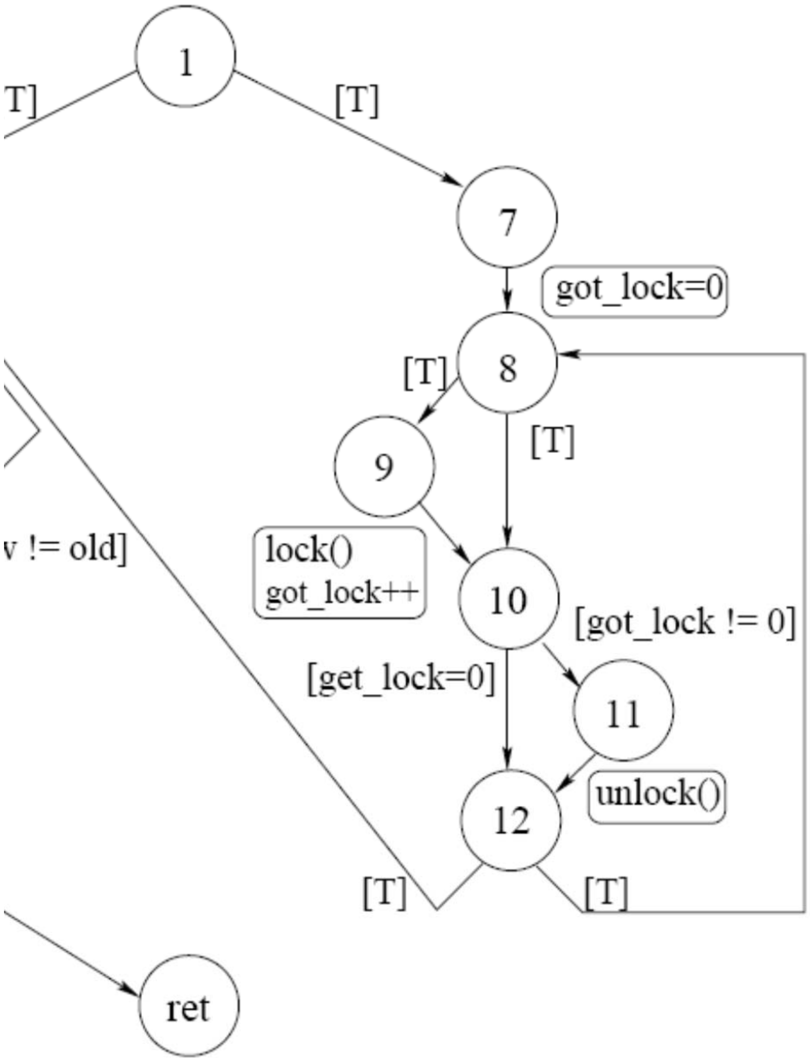
- Explore a subtree again
  - Start where new predicates were discovered
  - This time, track the new predicates
  - If the conjunction of the predicates on a node is false, stop exploring—this node is unreachable

Reanalysis Example





Analyzing the Right Hand Side



Generate Weakest Preconditions

- assume True;
- got_lock = 0;
- assume True;
- assume got_lock != 0;
- error (lock==0)

Why is the Error Spurious?

- More precisely, what predicate could we track that would eliminate the spurious error message?
- Consider, for each node, the constraints generated before that node (c1) and after that node (c2)
- Find a condition I such that
  - c1 => I
    - I is true at the node
  - I only contains variables mentioned in both c1 and c2
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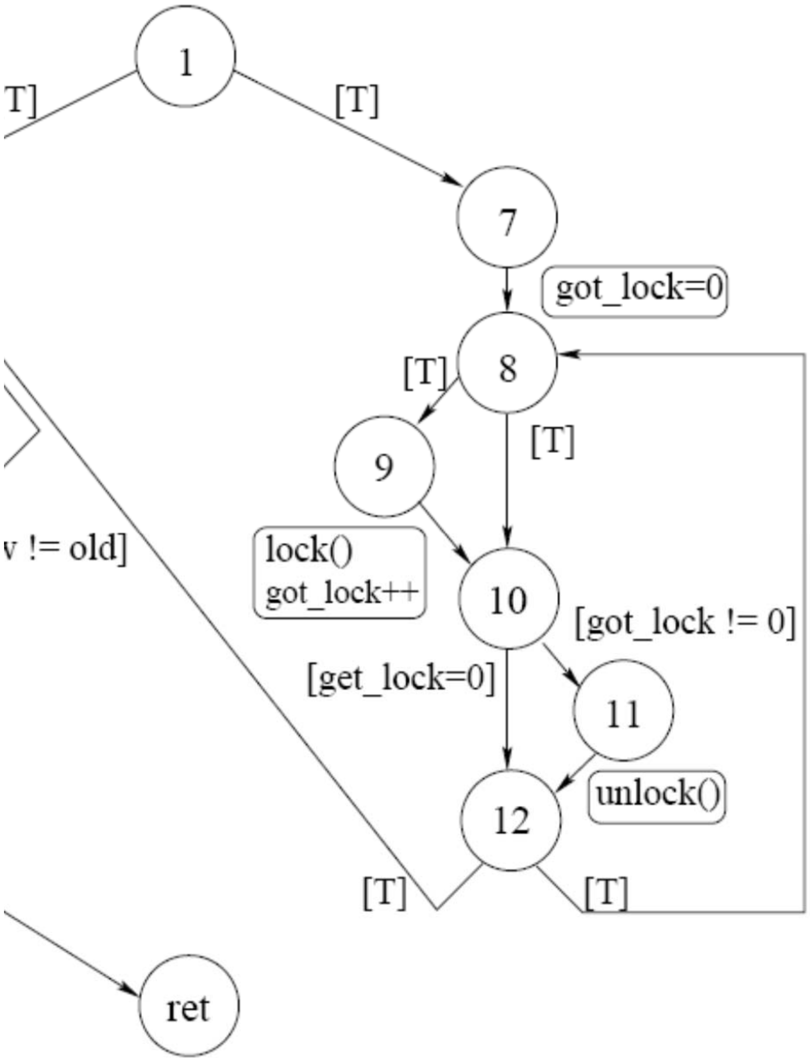
  - I $\wedge$ c2 = false
    - I is enough to show that the rest of the path is infeasible
  - I is guaranteed to exist
    - See Craig Interpolation

- $\wedge$ True
- $\wedge$ got_lock==0
- $\wedge$ True
- $\wedge$ got_lock!=0
- lock==0

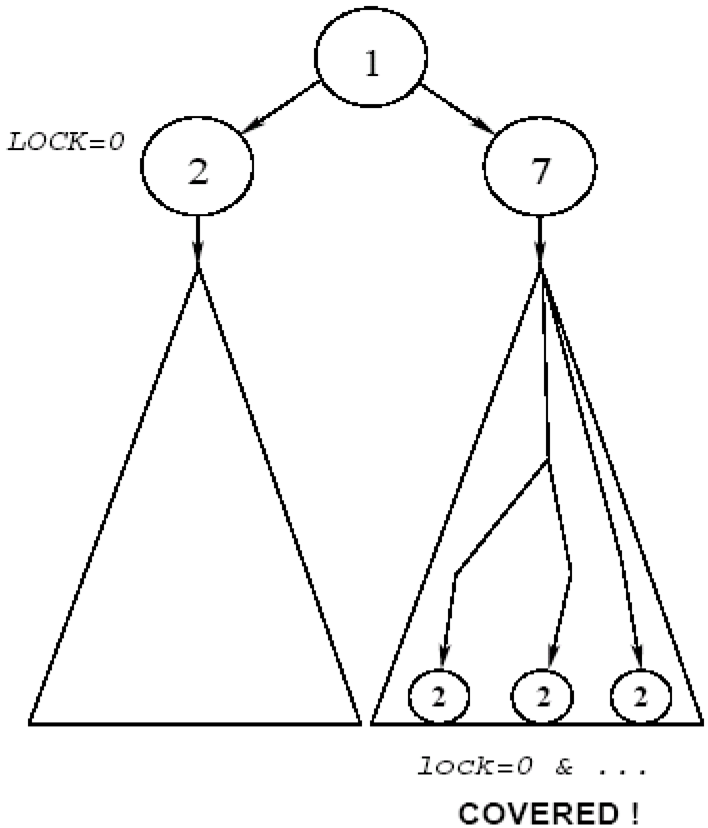
Reanalysis



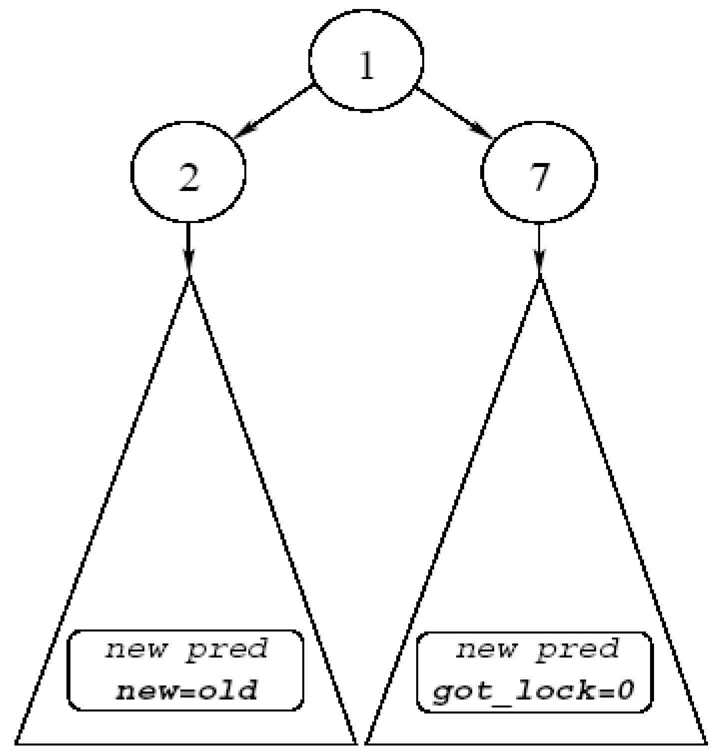
Key: L = locked=1
Z = got_lock=0

Blast Techniques, Graphically

- Explores reachable state, not all paths
  - Stops when state already seen on another path



- Lazy Abstraction
  - Uses predicates on demand
  - Only applies predicate to relevant part of tree



Termination

- Not guaranteed
  - The system could go on generating predicates forever
- Can guarantee termination
  - Restrict the set of possible predicates to a finite subset
    - Finite height lattices in data flow analysis!
  - Those predicates are enough to predict observable behavior of program
    - E.g. the ordering of lock and unlock statements
    - Predicates are restricted in practice
      - E.g. likely can't handle arbitrary quantification as in Dafny
      - Model checking is hard if properties depend on heap data, for example
  - Can't prove arbitrary properties in this case
- In practice
  - Terminate abstraction refinement after a time bound

Key Points of CEGAR

- To prove a property, may need to strengthen it
  - Just like strengthening induction hypothesis
- CEGAR figures out strengthening automatically
  - From analyzing why errors are spurious
- Blast uses *lazy abstraction*
  - Only uses an abstraction in the parts of the program where it is needed
  - Only builds the part of the abstract state that is reached
  - Explored state space is ***much*** smaller than potential state space

Experimental Results

Program	Postprocessed LOC	Predicates Total	Predicates Active	BLAST Time (sec)	Ctrex analysis (sec)	Proof Size (bytes)
qpmouse.c	23539	2	2	0.50	0.00	175
ide.c	18131	5	5	4.59	0.01	253
aha152x.c	17736	2	2	20.93	0.00	
tlan.c	16506	5	4	428.63	403.33	405
cdaudio.c	17798	85	45	1398.62	540.96	156787
floppy.c	17386	62	37	2086.35	1565.34	
[fixed]		93	44	395.97	17.46	60129
kbfiltr.c	12131	54	40	64.16	5.89	
		48	35	256.92	165.25	
[fixed]		37	34	10.00	0.38	7619
mouclass.c	17372	57	46	54.46	3.34	
parport.c	61781	193	50	1980.09	519.69	102967

Blast in Practice

- Has scaled past 100,000 lines of code
  - Realistically starts producing worse results after a few 10K lines
- Sound up to certain limitations
  - Assumes safe use of C
    - No aliases of different types; how realistic?
  - No recursion, no function pointers
  - Need models for library functions
- Has also been used to find memory safety errors, race conditions, generate test cases