Having a BLAST with SLAM

This is what I like about photography. People think cameras always tell the truth.

They think the camera is a dispassionate machine that records only facts, but really, cameras lie all the time. Select the facts and you manipulate the truth.

For example, I’ve cleared off this corner of my bed. Take a picture of me here, but crop out all the mess around me, so it looks like I keep my room tidy.

Is this even legal?

Wait, let me comb my hair and put on a tie.

If anyone hits me with a snowball, I’ll hit him with 250 snowballs!

What if somebody hits you with 250 snowballs?

...Sighhh...
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

“User applications must not run with root privilege”

When `execv` is called, must have `suid ≠ 0`
Property 3: IRP Handler

(IRP accessible)

- Start NP
- MPR completion
- Not pending returned
- Start P
- Mark Pending

(NP)
- MPR completion
- Skip
- Prop completion
- No prop completion

(SKIP1)
- CallDriver
- Skip

(SKIP2)
- CallDriver
- Return child status

(IPC)
- CallDriver
- Return not Pend

(N/A)
- CallDriver

(MPR3)
- Not pending returned

(MPR2)
- Not pending returned

(MPR1)
- CallDriver

[Sheehan]
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;
}

Diagram: Lock and Unlock机制示意图
SLAM in a Nutshell

\[
\text{SLAM}(\text{Program } p, \text{ Spec } s) = \text{Program } q = \text{incorporate_spec}(p, s); \quad \text{\texttt{// program}} \\
\text{PredicateSet } abs = \{ \}; \quad \text{\texttt{// slic}} \\
\textbf{while} \text{ true } \textbf{do} \\
\quad \text{BooleanProgram } b = \text{abstract}(q, abs); \quad \text{\texttt{// c2bp}} \\
\quad \text{match model_check}(b) \text{ with} \\
\qquad | \text{No_Error} \rightarrow \text{printf(“no bug”); exit(0)} \quad \text{\texttt{// bebop}} \\
\qquad | \text{Counterexample}(c) \rightarrow \\
\qquad \quad \text{if is_valid_path}(c, p) \text{ then} \\
\qquad \quad \quad \text{printf(“real bug”); exit(1)} \quad \text{\texttt{// newton}} \\
\qquad \quad \text{else} \\
\qquad \quad \quad abs \leftarrow abs \cup \text{new_preds}(c) \quad \text{\texttt{// newton}} \\
\text{done}
\]
Incorporating Specs

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

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; }

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 $\models$ logical formula
## Representing [Sets of States] as Formulas

<table>
<thead>
<tr>
<th>$[F]$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>states satisfying $F$ ${s \mid s \vDash F}$</td>
<td>FO fmla over prog. vars</td>
</tr>
<tr>
<td>$[F_1] \cap [F_2]$</td>
<td>$F_1 \land F_2$</td>
</tr>
<tr>
<td>$[F_1] \cup [F_2]$</td>
<td>$F_1 \lor F_2$</td>
</tr>
<tr>
<td>$\overline{[F]}$</td>
<td>$\neg F$</td>
</tr>
<tr>
<td>$[F_1] \subseteq [F_2]$</td>
<td>$F_1 \Rightarrow F_2$</td>
</tr>
</tbody>
</table>

i.e. $F_1 \land \neg F_2$ 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

3: unlock();
new++;}

4:

Theorem Prover

$\text{lock} \Rightarrow \text{old}=\text{new}$

$\neg \text{lock} \Rightarrow \neg \text{old}=\text{new}$
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

State

3: unlock();
    new++;
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

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

Solution
Use spurious counterexamples to refine abstraction

[Kurshan et al 93] [Clarke et al 00] [Ball-Rajamani 01]
Problem: Abstraction is Expensive

Problem

#abstract states = 2#predicates

Exponential Thm. Prover queries

Observe

Fraction of state space reachable

#Preds ~ 100’s, #States ~ $2^{100}$, #Reach ~ 1000’s
Solution 1: Only Abstract Reachable States

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

Exponential Thm. Prover queries

**Solution**

Don’t refine error-free regions
Q: Movies (416 / 842)

- This 1989 film features Robin Williams, suicide, school boys, barbaric yawps and "carpe diem".
In T.S. Eliot's 1939 Old Possum's Book Of Practical Cats, this "mystery cat is called the hidden paw / for he's a master criminal who can defy the law."
Complete these 1959 Clovers' song lyrics: "I didn't know if it was day or night / I started kissing everything in sight / but when I kissed a cop down on 34th and Vine / he broke my little ..."
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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Error Free

SAFE

S1: Only Abstract Reachable States
S2: Don’t refine error-free regions
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 ();
}
Build-and-Search

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

Predicates:  \textit{LOCK}

Reachability Tree
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
Example ( ) {
1:   do {
      lock();
      old = new;
      q = q->next;
      if (q != NULL){
        q->data = new;
        unlock();
        new ++;
      }while(new != old);
7: } while(new != old);
5:   unlock();
}
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Reachability Tree

Predicates: LOCK
Analyze Counterexample

Example ( ) {
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Predicates: LOCK

Reachability Tree
Analyze Counterexample

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

Reachability Tree

Predicates: LOCK

Inconsistent

new == old
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);
5:  unlock();
}

Predicates:  \textit{LOCK, new==old}
Repeat Build-and-Search

Example ( ) {
  do{
    lock();
    old = new;
    q = q->next;
    if (q != NULL){
      q->data = new;
      unlock();
      new ++;
    }
  }while(new != old);
  unlock();
}

Reachability Tree

Predicates:  LOCK, new==old
Repeat Build-and-Search

Example ( ) {

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

2: }while(new != old);
5: unlock();
}

Predicates:  \textit{LOCK}, \textit{new==old}

Reachability Tree
Repeat Build-and-Search

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

Predicates: \( \text{LOCK, new==old} \)

Reachability Tree

SAFE
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.

Error Free

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 ++;
3:   }
4:}while(new != old);
5: unlock () ;
}
Two handwaves

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

Q. How to compute “successors”? 

Reachability Tree

Predicates: LOCK, new==old

SAFE
Two handwaves

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

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 \( OP \)
Weakest Preconditions

\[
WP(P, OP)
\]

Weakest formula \( P' \) s.t.
if \( P' \) is true before \( OP \)
then \( P \) is true after \( OP \)

Assign
\[ x = e \]

\[
P[e/x]
\]

\[
new + 1 = old
\]
How to compute successor?

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();
}

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{
     lock();
     old = new;
     q = q->next;
2:     if (q != NULL){
3:       q->data = new;
         unlock();
       new ++;
     } while(new != old);
4: } while(new != old);
5:   unlock();
} 7

For each \( p \)
- Check if \( p \) is true (or false) after \( OP \)

Q: When is \( p \) false after \( OP \) ?
- If \( WP(\neg p, OP) \) 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?

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();
}

For each \( p \)
- Check if \( p \) is true (or false) after \( \text{OP} \)

Q: When is \( p \) false after \( \text{OP} \)?
- If \( \text{WP}(\neg \ p, \text{OP}) \) is true before \( \text{OP} \)
- We know \( F \) is true before \( \text{OP} \)
- Thm. Pvr. Query: \( F \Rightarrow \text{WP}(\neg \ p, \text{OP}) \)

Predicate: \( \text{new==old} \)

True ? \( (\text{LOCK} , \text{new==old}) \Rightarrow (\text{new + 1 = old}) \) \ NO

False ? \( (\text{LOCK} , \text{new==old}) \Rightarrow (\text{new + 1 \neq old}) \) \ 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, ¬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 = 23454567
- [x=0, ¬x+2≠88, x+2<77]
- Preds = {x=0,x+1=88,x+2=88}
- Path = 2345454567
- ...
- Result: the predicates “count” the loop iterations
Homework

- Read Winskel Chapter 2
- Read Hoare paper
- Read Optional papers