Efficient Elimination of False Positives using Static Analysis

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International Symposium on Software Reliability Engineering
November 2-5, 2015
Gaithersburg, MD, USA
Background

- Static analysis - scalable but imprecise
- Model checking - precise but not scalable
- Static analysis + model checking ⇒ better results
- **False positives elimination using model checking**\(^1\)
  - Generate an assertion corresponding to each warning
  - Verification in incremental context
  - Scalable to some extent but a lot many model checking calls
  - Time consuming

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\(^1\)Hendrik Post et al. “Reducing False Positives by Combining Abstract Interpretation and Bounded Model Checking”. In: *ASE*. 2008, pp. 188–197.
A Motivating Example

```c
const int arr[] = {0, 2, 5, 9, 14};
int var, factor; char ch;

void f1()
{
    unsigned int i, j;

    i = lib1();
    j = lib2();
    var = lib3();

    if (j < 5 && i < j)
    {
        factor = arr[j] - arr[i];
        f2();
    }
}
```

```c
int f2()
{
    if (var == factor)
        f3(var);
    ...
}
```

```c
int f3(int p)
{
    int a, b, denom = 1;
    if (ch < 5)
    {
        denom = p;
    }
    else
    {
        denom = 10;
    }
    assert(denom != 0);
    a = 100/denom; //warning
}
```
Context Expansion: Call 1

Verifying the assertion in the context of $f3$ results in Counterexample by assigning 0 to $p$

```c
p = nondet_int();
ch = nondet_char();

int f3(int p){
    int a, b, denom=1;
    if(ch < 5)
        denom = p;
    else
        denom = 10;
    assert(denom!=0);
    a = 100/denom;  //warning
}
```
Context Expansion: Call 2

```c
var = nondet_int();
factor = nondet_int();
ch = nondet_char();

int f2()
{
    if(var==factor)
        f3(var);
    ...
}

int f3(int p)
{
    int a, b, denom=1;
    if(ch < 5)
        denom = p;
    else
        denom = 10;
    assert(denom!=0);
    a = 100/denom; //warning
}
```

Verifying the assertion in the context of $f_2$ results in Counterexample by assigning 0 to $\text{var}$ and $\text{factor}$
Context Expansion: Call 3

Assertion holds when verified in the context of $f1$.

```c
ch = nondet_char();

const int arr[] = {0, 2, 5, 9, 14};

void f1() {
    unsigned int i, j;

    i = lib1();
    j = lib2();
    var = lib3();

    if (j < 5 && i < j) {
        factor = arr[j] - arr[i];
        f2();
    }
}
```

```c
int f2() {
    if (var == factor)
        f3(var);
    ...
}
```

```c
int f3(int p) {
    int a, b, denom = 1;
    if (ch < 5)
        denom = p;
    else
        denom = 10;
    assert(denom != 0);
    a = 100/denom; //warning
}
```
Motivation

➤ The problem
  ➤ Large number of model checking calls
  ➤ Hence, time consuming

➤ Observation
  ➤ If any arbitrary value is allowed for an assertion variable at the assertion point, the assertion verification results in a counterexample.
Our Approach

- **Complete-range Non-deterministic Value (cnv) variables**
  - Taking complete-range of non-deterministic values
  - Any arbitrary value is allowed
  - No value assignment/restriction through program code

- **Complete-range Non-deterministic Value (cnv) expressions**
  - \((x + 10), (x + +), \) and \((x + y)\) are *cnv* expressions when \{x, y, z\} are *cnv* variables.
  - \((x + 10), \) and \((x + +)\) are **not** *cnv* expressions when \{y, z\} are *cnv* variables.
  - \((x/100), (x\%2), \) and \((100)\) in n **are not** *cnv* expressions even if x is a *cnv* variable.

- **Identify redundant verification calls (RVCs) and skip them**
  - using cnv variables
Computation of cnv variables

- Depends on
  - Context sensitivity
  - Flow sensitivity
  - May/Must reachability
  - Data and control dependance

- Using Data Flow Analysis
  - Lattice structure

```cpp
void f(int x) {
    //x ↦ CNV
    if (x < 10) {
        //x ↦ nCNVₜ
    } else {
        //x ↦ nCNVₕ
    }
    //x ↦ CNV
}
```

(a) May cnv variables

(b) Must cnv variables
RVCs Identification

If all assertion variables are \textit{cnv} variables, the call is redundant.

```c
const int arr[] = {0, 2, 5, 9, 14};
int var, factor; char ch;

void f1(){
  unsigned int i, j;
  i = lib1();
  j = lib2();
  var = lib3();
  if(j < 5 && i < j){
    factor = arr[j] - arr[i];
    f2();
  }
}

int f2(){
  if(var == factor )
    f3(var);
    ...
}

int f3(int p){
  int a, b, denom=1;
  if(ch < 5)
    denom = p;
  else
    denom = 10;
  assert(denom != 0);
  a = 100/denom; // warning
}
```
Influence of cnv variables

```c
void foo()
{
  b = 0;

  if(v == 1)
  {
    a = 10;
    b = 10;
  }

  if(v == 1)
  {
    assert(a != 0); // May Vs Must
  }

  if(b == 10)
  {
    assert(v != 0); // O-AEP
  }

  if(x < 100)
  {
    assert(x < 10); // Insufficiency
  }
}
```

- Is RVCs identification accurate?
  - *may-cnvs* variables Vs *must-cnvs* variables
  - Impact of over-approximation of execution paths (O-AEP)
  - Insufficiency of *cnv* variables

- Define two parameters
  - Precision = \( \frac{\text{number of correctly identified RVCs}}{\text{total number of identified RVCs}} \)
  - Recall = \( \frac{\text{number of correctly identified RVCs}}{\text{number of actual calls violating the assertions}} \)
Effect on False Positives Elimination

Define two parameters

- **Time saving** = 1 - \( \frac{\text{Time taken in } eFPE}{\text{Time taken by } FPE_{\text{orig}}} \)

- **Elimination loss** = 1 - \( \frac{\text{False positives eliminated in } eFPE}{\text{False positives eliminated by } FPE_{\text{orig}}} \)

Trade-off

- Precision Vs Recall
- Time saving Vs Elimination loss
Experimental Set up

- \textit{cnv} variables computation - implementation in TCS ECA\(^2\)
- CBMC as the model checker\(^3\)
- Two applications (50 KLOC and 40 KLOC)
- Two properties (DZ and AIOB)
- False positives elimination in three settings
  - \textit{FPE}_\text{orig}, \textit{eFPE}_\text{may}, and \textit{eFPE}_\text{must}
- Each setting with two context levels
  - maxCCL = 1, and maxCCL = 5
- Assumptions
  - assertions are reachable
  - code is sliced and every slice corresponds to a single assertion

\(^2\)TCS Embedded Code Analyzer (TCS ECA).  

\(^3\)CBMC.  http://www.cprover.org/cbmc/.
Experimental Results

Total model checking calls

Model checking calls resulting in counter-examples
Experimental Results

False positives elimination time

False positives eliminated by FPE settings
Observations

- RVCs identification
  - 76% recall with 97.3% precision
  - Total model checking calls reduced by 49.49%
  - Calls resulting in counterexamples
    - original-FPE=58%, efficient-FPE=31%

- False positives elimination time reduced by 39.28%
  - Missed elimination of 21/754 false positives

- Trade-off:
  - Efficiency 39.28% Vs Elimination loss 2.78%
  - Failed cases require manual reviewing

- Constraining over One Vs All assertion variables
  - both choices applicable in practice
Summary

- **The problem**
  - large number of model checking calls
  - poor performance in false positives elimination

- **Our Solution**
  - Introduced a concept of $cnv$ variables
  - Identification of redundant verification calls

- **Experimental evaluation**
  - Trade-off: Efficiency (39.28%) Vs Elimination loss (2.78%)
  - Spectrum of trade-offs
    - May Vs Must $cnv$ variables
    - Single Vs Multiple variables
  - Choice depending on requirement in practice
Thank you!

Questions or Suggestions?

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