Targeted Program Transformations for Symbolic Execution

Cristian Cadar

Software Reliability Group

Department of Computing

Imperial College London

ESC/FSE New Ideas Track **2nd September 2015**

Background:
Dynamic Symbolic Execution

Program analysis technique for ***automatically exploring paths*** through a program

- Determines the feasibility of each explored path using a *constraint solver*
- For each path, can generate a *concrete input triggering the path*

Dynamic Symbolic Execution

Received significant interest in the last few years

Many dynamic symbolic execution/concolic tools available as open-source:

- CREST, KLEE, SYMBOLIC JPF, etc.

Started to be adopted/tried out in the industry:

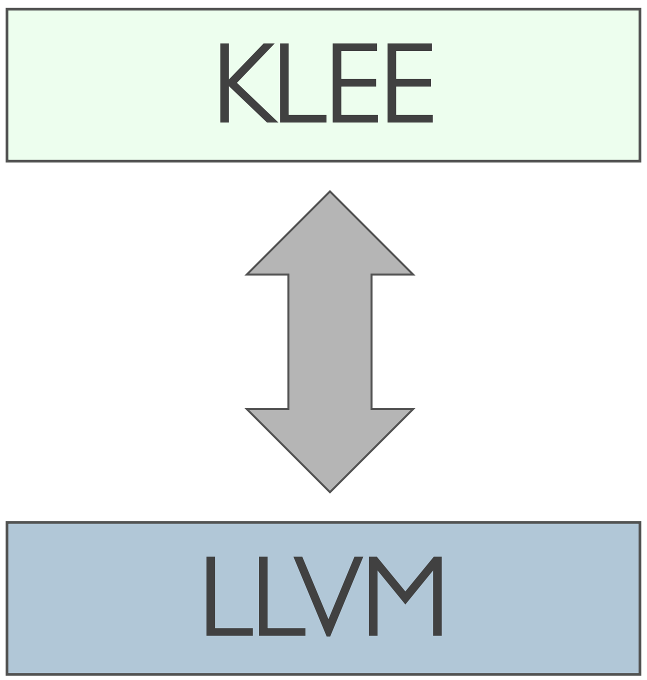
- SAGE (Microsoft)
- SYMBOLIC JPF (NASA, Fujitsu, etc.)
- KLEE (Fujitsu, Hitachi, Citrix, etc.)
- APOLLO (IBM), etc. etc.

KLEE [http://klee.github.io]

Popular open-source engine:

- 1000+ clones per month
- 100+ forks on GitHub
- Many popular systems built on top of it (KleeNet, Cloud9, GKLEE, KLEE-MultiSolver, etc.)
- Lots of research ideas explored using KLEE as a platform

KLEE and LLVM



<u>Weird phenomenon</u>

Changing LLVM versions would sometimes result in HUGE performance differences

*Performance of symbolic execution can vary dramatically across **semantically-equivalent** programs*

To precompute or not to precompute

Unoptimized

```
int get_value(int k){
    return k * k * k;
}

// precond: k < 1000
int foo(unsigned k) {
    if (get_value(k) > 100000 ||
        get_value(k-1) > 100000)
       return 0;
    else return 1;
}
```

Optimized

```
int values[1000] = {0, 1, 8,
27, 64, 125, 216, 343, 512,
729, 1000, 1331, 1728, ... };

int foo(unsigned k) {
    if (values[k] > 100000 ||
        values[k-1] > 100000)
       return 0;
    else return 1;
}
```

0.2s vs. 50s

250x slower!

$k^3 > 100{,}000$

vs.

values[k] > 100,000 ∧
values[0] = 0 ∧
values[1] = 1
∧ ...

To -O2 or not to -O2

Compiler optimisations example

```
int bar(int a[10]) {
    int count=0, i;
    for (i=0; i<10; i++)
        if (a[i] > 0)
            count++;
    if (count == 10)
        printf ("Success\n");
    return count;
}
```

```
-O0: 23s
-O2: 0.04s (575x faster!)
```

Explanation:

–O2 transforms the if into a select(a[i]>0, count+1, count) which KLEE sends directly to the solver

Essentially –O2 has merged the paths inside the loop

KLEE 6118403fa4 with LLVM 2.9, STP 1668, on Intel Core2 Duo CPU E8400 at 3.00GHz, Ubuntu 14.04

How do I switch this?

Switch example

```
int expensive(int x) {
    int bits = 0, i;
        for (i=0; i<< i))
            bits++;
    return bits;
}

int foo(int x, int y) {
    switch (x) {
      case 1: return expensive(y+1);
      case 2: return expensive(y+2);
      case 3: return expensive(y+3);
      case 4: return expensive(y+4);
      default: return x/y;
    }
}
```

Binary search: 23s to bug
Linear search: TIMEOUT 1h

KLEE 6118403fa4 with LLVM 2.9, BFS, STP 1668, Intel Core2 Duo CPU E8400 at 3.00GHz, Ubuntu 14.04

Testability transformations
= key ingredients in symex

Testability Transformations for SymEx

Semantics-preserving	*Semantics-altering*
• *Developers (optimisations, refactorings)*	• *Approximations (reals instead of FP)*
• *Compilers (optimisations, code generation)*	• *Shrinking large memory objects*
• *Choice of abstraction (source, binary, intermediate language, etc.)*	• *Assigning concrete values to part of the input*

Testability transformations introduced in the context of SBST by Harman et al. [TSE 2004]

Could enable symex to scale to larger applications

Faster constraint solving

- E.g., precomputed lookup example

More targeted path exploration

- E.g., path merging examples

More application types

- E.g., floating point code

More generally, can we:

- **write programs friendly to symex analysis?**
- **automatically transform programs to be symex-friendly?**

Essential for understanding ongoing research ideas/experiments

Case study 1: paper reporting10x improvement in performance on top of some prior KLEE experiments. Is this due to:

(a) the technique itself

(b) different LLVM versions

(c) different compiler options

Case study 2: study reporting a 10x performance difference between KLEE and CREST. Is this due to:

(a) the techniques in KLEE vs CREST

(b) the intermediate language used by LLVM and CIL

(c) different compiler optimisations being performed

Conclusion

Testability transformations should be a key ingredient in symex. We should:

- **Account for them:** essential for understanding ongoing research ideas and experiments in this area
- **Understand them:** improve performance by carefully enabling and disabling existing transformations such as compiler optimisations
- **Provide guidelines for writing symex-friendly code:** similar in spirit to existing interactive verifiers
- **Design targeted transformations:** both semantics-preserving and semantics-altering, and addressing both constraint solving and path exploration challenges

Looking for postdoc applicants
to work in this area:
http://srg.doc.ic.ac.uk/vacancies/

Imperial College London

SOFTWARE RELIABILITY GROUP