Today

Last lecture

• VC generation with weakest liberal preconditions

Today

• Symbolic execution: strongest postconditions for finite programs
• Concolic testing
The spectrum of program validation tools

Confidence

Cost (programmer effort, time, expertise)

- Ad-hoc Testing
- Concolic Testing & Whitebox Fuzzing
- Bounded Verification & Symbolic Execution
- Extended Static Checking
- Static Analysis
- Verification
The spectrum of program validation tools

- **Static Analysis**
- **Verification**
- **Extended Static Checking**
- **Bounded Verification & Symbolic Execution**
- **Concolic Testing & Whitebox Fuzzing**
- **Ad-hoc Testing**

**Examples:**
- Static Analysis: E.g., JPF, Klee
- Verification: E.g., SAGE, Pex, CUTE, DART

*Cost (programmer effort, time, expertise)* 
*Confidence*
A brief history of symbolic execution

1976: A system to generate test data and symbolically execute programs (Lori Clarke)

1976: Symbolic execution and program testing (James King)

2005-present: practical symbolic execution

- Using SMT solvers
- Heuristics to control exponential explosion
- Heap modeling and reasoning about pointers
- Environment modeling
- Dealing with solver limitations
Symbolic execution: basic idea

def f(x, y):
    if (x > y):
        x = x + y
        y = x - y
        x = x - y
    if (x - y > 0):
        assert False
    return (x, y)
Symbolic execution: basic idea

```python
def f(x, y):
    if (x > y):
        x = x + y
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        x = x - y
    if (x - y > 0):
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Execute the program on symbolic values.
Symbolic execution: basic idea

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*Symbolic state* maps variables to symbolic values.
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*Path condition* is a quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far.

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Execute the program on symbolic values.

Symbolic state maps variables to symbolic values.

Path condition is a quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far.

All paths in the program form its execution tree, in which some paths are feasible and some are infeasible.
Symbolic execution: basic idea

Execute the program on *symbolic values*. 

*Symbolic state* maps variables to symbolic values.

*Path condition* is a quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far.

All paths in the program form its *execution tree*, in which some paths are *feasible* and some are *infeasible.*

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Execute the program on symbolic values.  
Symbolic state maps variables to symbolic values.  
Path condition is a quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far.  
All paths in the program form its execution tree, in which some paths are feasible and some are infeasible.
Symbolic execution: practical issues

Loops and recursion: infinite execution trees

Path explosion: exponentially many paths

Heap modeling: symbolic data structures and pointers

Solver limitations: dealing with complex PCs

Environment modeling: dealing with native / system / library calls
Loops and recursion

Dealing with infinite execution trees:

- Finitize paths by unrolling loops and recursion (bounded verification)
- Finitize paths by limiting the size of PCs (bounded verification)
- Use loop invariants (verification)
Loops and recursion

Dealing with infinite execution trees:

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- Finitize paths by limiting the size of PCs (bounded verification)
- Use loop invariants (verification)

```c
init;
while (C) {
    B;
}
assert P;
```
Loops and recursion

Dealing with infinite execution trees:

- Finitize paths by unrolling loops and recursion (bounded verification)
- Finitize paths by limiting the size of PCs (bounded verification)
- Use loop invariants (verification)

init;
while (C) {
    B;
}
assert P;

init;
assert I;
havoc targets(B);
assume I;
if (C) {
    B;
    assert I;
    assume false;
}
assert P;
Path explosion

Achieving good coverage in the presence of exponentially many paths:

• Select next branch at random
• Select next branch based on coverage
• Interleave symbolic execution with random testing
Path explosion

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Heap modeling

Modeling symbolic heap values and pointers

- Bit-precise memory modeling with the theory of arrays (EXE, Klee, SAGE)
- Lazy concretization (JPF)
- Concolic lazy concretization (CUTE)
class Node {
    int elem;
    Node next;
}

n = symbolic(Node);
x = n.next;
Heap modeling: lazy concretization

```java
class Node {
    int elem;
    Node next;
}

n = symbolic(Node);
x = n.next;
```
Heap modeling: lazy concretization

class Node {
    int elem;
    Node next;
}

n = symbolic(Node);
x = n.next;

A0

A0.next = null

n \mapsto \text{A0}

x \mapsto \text{null}

A0

elem: ?

next: null

elem: ?

next: ?
Heap modeling: lazy concretization

class Node {
    int elem;
    Node next;
}

n = symbolic(Node);
x = n.next;

A0

\[
\begin{align*}
\text{n} & \mapsto \text{\textbf{A0}} \\
\text{x} & \mapsto \text{null}
\end{align*}
\]

A0

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\text{x} & \mapsto \text{\textbf{A0}}
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Heap modeling: lazy concretization

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n = symbolic(Node);

x = n.next;

A0.next = null
A0.next = A0
A0.next = A1

A0

elem: ?
next: null

A0

elem: ?
next: A0

A0

elem: ?
next: A1

A0

elem: ?
elem: ?
next: A0
next: ?

A0

elem: ?
elem: ?
next: A1
next: ?
typedef struct cell {
    int v;
    struct cell *next;
} cell;

int f(int v) {
    return 2*v + 1;
}

int testme(cell *p, int x) {
    if (x > 0)
        if (p != NULL)
            if (f(x) == p->v)
                if (p->next == p)
                    assert false;
    return 0;
}
Heap modeling: concolic testing

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  return 0;
}

Concrete
p := null
x := 236

PC
x > 0 ∧ p=null

Execute concretely and symbolically. Negate last decision and solve for new inputs.
Heap modeling: concolic testing

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Execute concretely and symbolically. Negate last decision and solve for new inputs.
Solver limitations

Reducing the demands on the solver:

- On-the-fly expression simplification
- Incremental solving
- Solution caching
- Substituting concrete values for symbolic in complex PCs (CUTE)
Environment modeling

Dealing with system / native / library calls:

- Partial state concretization
- Manual *models* of the environment (Klee)
Summary

Today

• Practical symbolic execution and concolic testing

Next lecture

• Angelic execution