

CS1632, Lecture 15: Static Analysis, Part 2

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Kinds of Static Tests

- Code review / walk-through
- Compiling
- Code coverage
- Code metrics
- Linters
- Bug finders
- Formal verification

Formal Verification

- Proving one or the other about a program:
 - Program has no defect
 - Program has defects (and find all of them)
- What!?



Holy Grail of Formal Verification

- Soundness
 - If no defect is reported, then the program does not fail
 - No false negatives
- Preciseness
 - If a defect is reported, then the program does fail
 - No false positives
- Termination
 - The verification terminates

It is impossible to achieve the holy grail in general!

Formal Verification is Undecidable

$x \in \text{Variable}$

$P \in \text{Program} = \text{assert } x \mid x++ \mid x-- \mid$
 $P_1 ; P_2 \mid \text{if } x \text{ then } P_1 \text{ else } P_2 \mid \text{while } x \text{ } P$

- Assertion checking for even this simple language is undecidable!
- “The **Halting Problem** cannot be solved for *all* possible programs (for a Turing-complete language)” - *Alan Turing (1936)*
- Silver-lining: But for *some* programs it can be solved



Methods of Formal Verification

- Theorem Proving
 - Deducing postcondition from precondition through mathematical formal methods
- Model Checking
 - Given a finite state model of a system, exhaustively checking whether this model meets a given specification

Theorem Proving

Deducing postcondition from precondition through
mathematical formal methods

Hoare Logic Theorem Proving

- Hoare Logic: Deduces postcondition from precondition through math
- Hoare Triplet: {Precondition} Program {Postcondition}
 - Meaning: Given Precondition and Program, Postcondition is always true
- Examples of Hoare Triplets:
 - { true } $x := 5$ { $x == 5$ }
 - { $x == y$ } $x := x + 3$ { $x == y + 3$ }
 - { $x == a$ } if ($x < 0$) then $x := -x$ { $x == |a|$ }
 - { $x < 0$ } while ($x != 0$) $x := x - 1$ { ??? } \leftarrow No such triple!

Hoare Logic Syntax

- Idea is to use this syntax to prove with pen and paper your program is correct
- Sounds unappealing? ☹️
 - Many programmers would agree!
- There exist “theorem provers” that automate mundane parts of proving
 - But needs human assistance at difficulties
 - Example difficulty: reasoning about recursive data structures (lists, trees, ...)

Theorem Proving Advantages

- Can prove large programs with infinite states
 - Remember this Hoare triplet?
`{ x < 0 } while (x!=0) x := x-1 { ??? }`
 - Model checker will have trouble because it has an infinite number of states
 - But a human or machine theorem prover can tell there is an infinite loop!
- Leads programmer to a deeper understanding of the program
 - After spending weeks proving the program is correct, a natural outcome
 - But really, it does lead to some fundamental insights about your program

Theorem Proving Disadvantages

- Requires (a lot of) human involvement
 - Every time a theorem prover encounters difficulty humans have to step in
 - Requires many hours of highly skilled labor to complete a proof
 - Humans also make mistakes
- Proofs can be obscenely long
 - In one report by Motorola, a proof was 25 MB long (more than 100 pages)
 - Beyond the comprehension limits of a normal human being

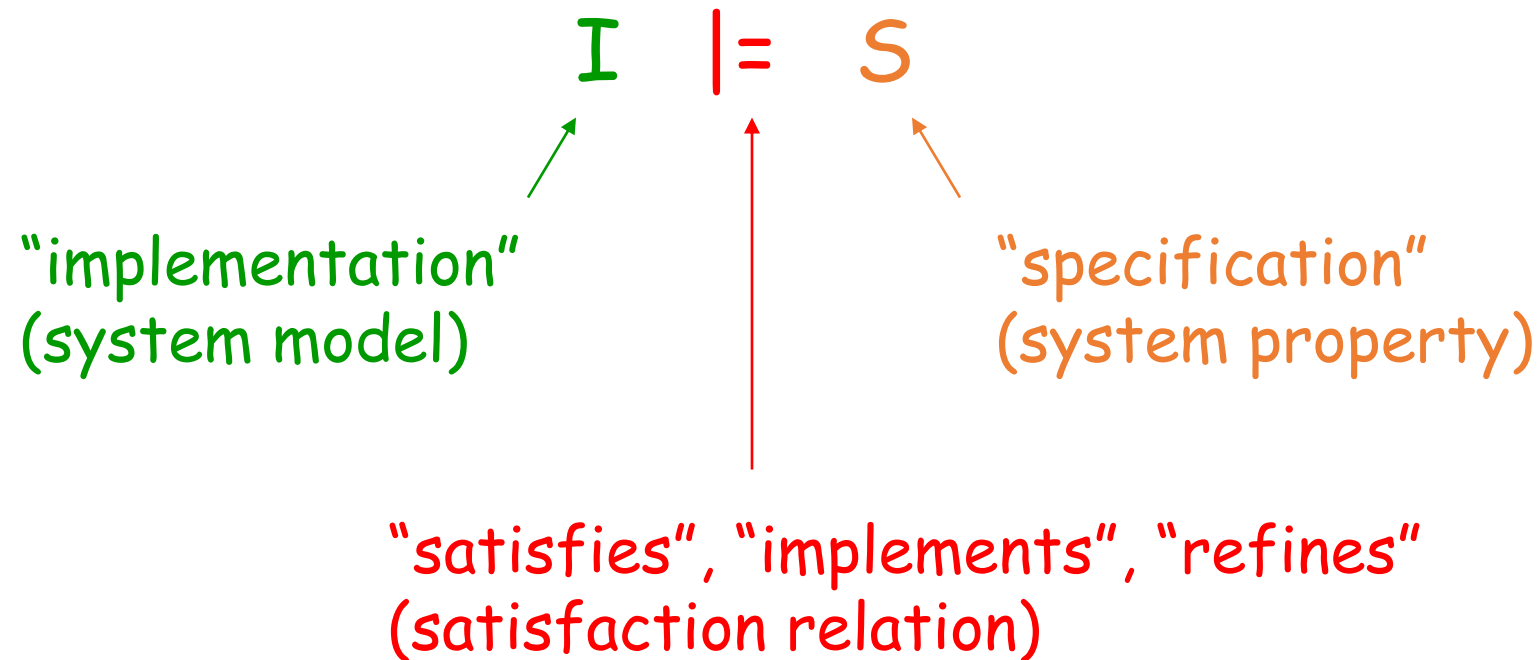
Industry Reception

- Advocates want a “formal methods guru” on every project team
 - The education required to produce a “formal methods guru” is very different from the education of a typical software engineer
- Naturally, industry is resistant
- Used in niche markets where correctness is paramount
 - Some embedded systems, cryptography libraries, OS kernels (seL4)
- Industry would like a “push button” solution
 - something that Model Checking provides!

Model Checking

Given a finite state model of a system, exhaustively checking whether this model meets a given specification

The Model Checking Problem



Examples of System Properties

- Assertions (invariants)
 - Embedded in source code or part of property-based unit test
- Memory related properties
 - No leaks, double-free, access after free
 - No reading of uninitialized variables
 - No out of bounds array accesses
- Other resource related properties
 - No resource leaks: CreateFile followed by DeleteFile
 - No write of private data to insecure public resources

Comparison with Property-Based Testing

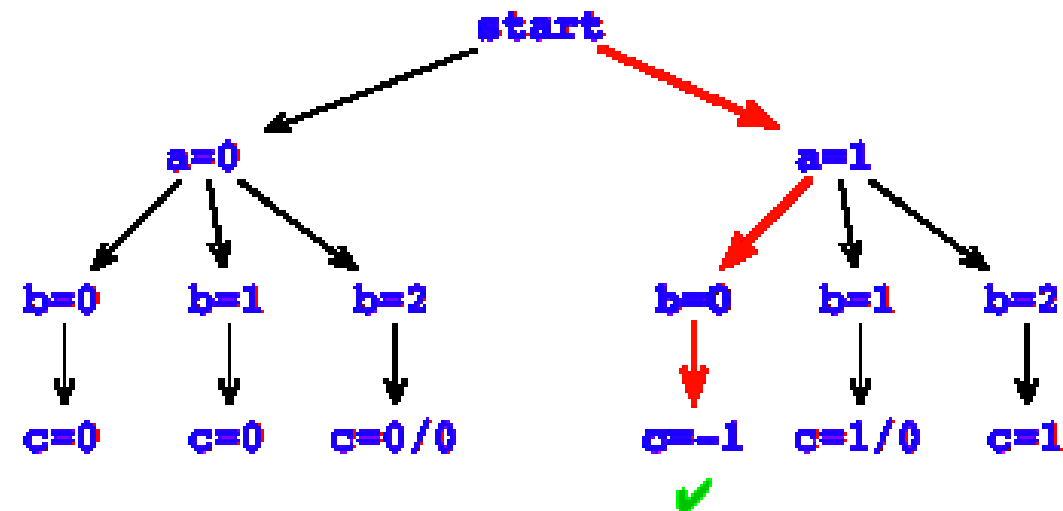
- Similarity
 - Model checking also tests a property, not an output value
- Difference
 - With stochastic testing, we tested (a few) randomized input values
 - With model checking, all states are check *exhaustively*
 - With model checking, states are visited in a *systematic* way

Stochastic Testing (a Single Trial)

Given this code:

```
int a = random.nextInt(2);  
int b = random.nextInt(3);  
int c = a / (b + a - 2);
```

If unlucky, bug is never found!



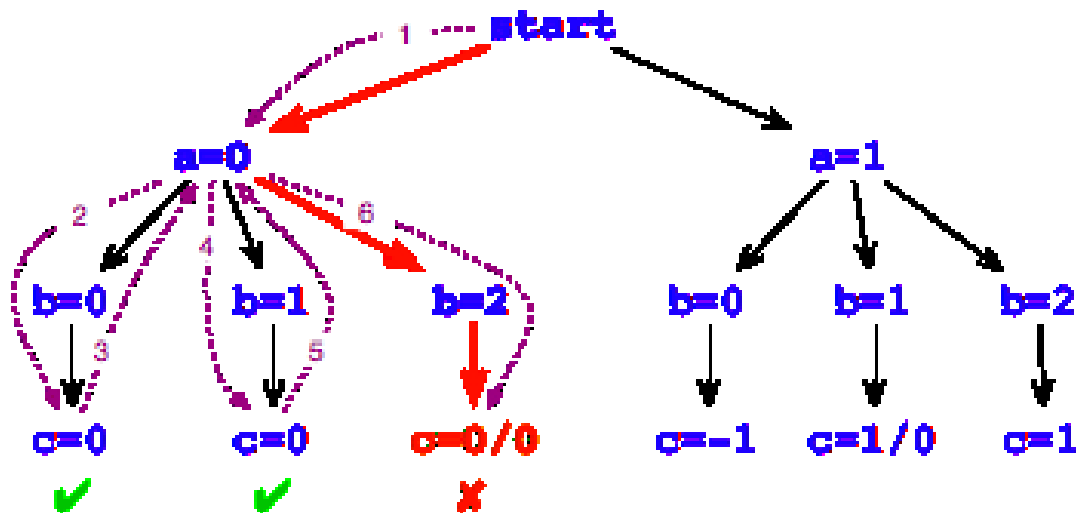
- ① `Random random = new Random();`
- ② `int a = random.nextInt(2);`
- ③ `int b = random.nextInt(3);`
- ④ `int c = a / (b + a - 2);`

Model Checking

Given this code:

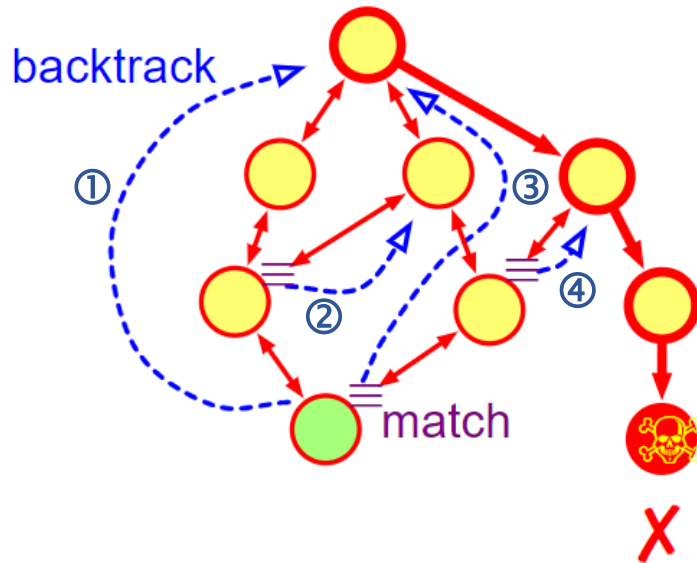
```
int a = random.nextInt(2);  
int b = random.nextInt(3);  
int c = a / (b + a - 2);
```

Bug is always found!
(through exhaustive searching)
If none found, guaranteed correct!



```
Random random = new Random();  
  
int a = random.nextInt(2)  
  
int b = random.nextInt(3)  
  
int c = a / (b + a - 2)
```

Systematic Exploration



Circles: Program states
Arrows: State transitions

- Example of depth-first-search of state space
- State transitions happen as a result of executing a program statement
- Backtrack
 - On termination or when there is a match
 - Go to a previous state with unexplored transitions
- Match
 - When next state matches a previously visited state
 - Backtrack to not waste work

Systematic Exploration Algorithm

```
Hashtable states_seen;
```

```
Queue pending;
```

```
pending.add(initial_state);
```

```
while(!pending.empty()) {
```

```
    current = pending.remove();
```

```
    if(current in states_seen)
```

```
        continue;    // match! Backtrack.
```

```
    check current for correctness;
```

```
    states_seen.insert(current);
```

```
    for transition T in current {
```

```
        successor = execute transition T on current;
```

```
        pending.add(successor);
```

```
        restore_state(current);
```

```
    }
```

```
}
```

State Explosion Problem

- States num = $O(D^N)$, where N = variables, D = data type domain size
 - E.g. if there are N Boolean variables, number of states = 2^N
- You may even end up with an *infinite* number of states
 - If your program has the potential to create an infinite number of objects
- Single reason preventing wide adoption of model checking
 - May run into memory limitations (can't contain entire state graph)
 - State exploration may take too long to be usable
 - Especially a big problem for sizable programs (> 10,000 lines of code)

Concrete and Abstract Model Checking

- Concrete model checking
 - States in model are actual concrete program states
 - As in, your program stack and your program heap
- Abstract model checking
 - States in model are some abstraction of actual program states
 - Abstraction is done in hopes of reducing the state explosion problem
 - Typically tradeoffs accuracy for efficiency

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Abstract Model Checking

- Requires an intermediate description of abstract model
 - Describes the system at a high level
 - Throws away implementation details
- Good for checking designs, rather than implementations
 - Success stories: hardware circuits, cache-coherence protocols
- Problem: Specifying an abstract model is HARD for large systems
 - What you check is not what you run!
 - As the system evolves model has to be updated
 - Manual extraction of abstract model can miss or introduce errors

Automatically Extracting the Model

- Statically analyze the code to generate a model
 - Models usually mimic the implementation

Murphi abstract model

```
Rule "PI Local Get (Put)"
  1: Cache.State = Invalid
    & ! Cache.Wait
  2: & ! DH.Pending
  3: & ! DH.Dirty ==>
    Begin
  4: Assert !DH.Local;
  5: DH.Local := true;
  6: CC_Put(Home, Memory);
  EndRule;
```

Flash Memory Driver Implementation

```
void PILocalGet(void) {
    // ... Boilerplate setup
  2  if (!hl.Pending) {
  3    if (!hl.Dirty) {
  4!    // ASSERT(hl.Local);
        ...
  5    hl.Local = 1;
  6    PI_SEND(F_DATA, F_FREE, F_SWAP,
              F_NOWAIT, F_DEC, 1);
}
```

Automatic Model Extraction

- Examples
 - FeaVer : C program -> Promela (SPIN) model
 - Bandera: Java -> Bandera model
- Features
 - Sophisticated property-driven slicing techniques
 - Can throw away state unrelated to property that is being proved
- Problems
 - Not all primitives are available in the modeling language
 - Pointers, dynamic object creation, dynamic threads, exceptions
 - A precise-enough slice could be as large as the program itself

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Concrete Model Checking

- Code as the model – directly execute the code!
- Concrete model checkers
 - Verisoft (C/C++) – Bell Laboratories
 - CBMC (C/C++) – Oxford University
 - Java Path Finder (Java) – NASA
- State space can be infinite (or very large)
 - Try exploring as much behaviors as possible (likely you can't explore all)
 - Focus on precision (finding defects accurately)

State Space and Programming Language

- Definition of program state depends on programming language
 - What is the state that your program can access and modify?
- C/C++ programs: essentially your entire memory space!
- Java programs: abstract state maintained by the Java Virtual Machine
 - Java bytecode works on an abstract stack maintained by JVM + heap
 - That state is *much* smaller than your entire memory space
 - Gets some benefits of abstract model checking while still being concrete!

State Space and Programming Language

- Remember I said choice of language is important?
 - This is one example: it is much easier to model check Java than C/C++!
- Fortunately, you can convert most languages to Java bytecode
 - JavaScript, Python, Ruby, Lua, ...
 - Even (for a limited set of) C / C++
 - And then, you can model check the bytecode using a JVM
 - But not equivalent since at deployment it will not execute as Java bytecode
- But regardless, state space grows *very* quickly

State Space Reduction Techniques

- State collapsing
- Heuristic state approximation
- Hash compaction
- Heap canonicalization
- Symbolic execution

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State collapsing

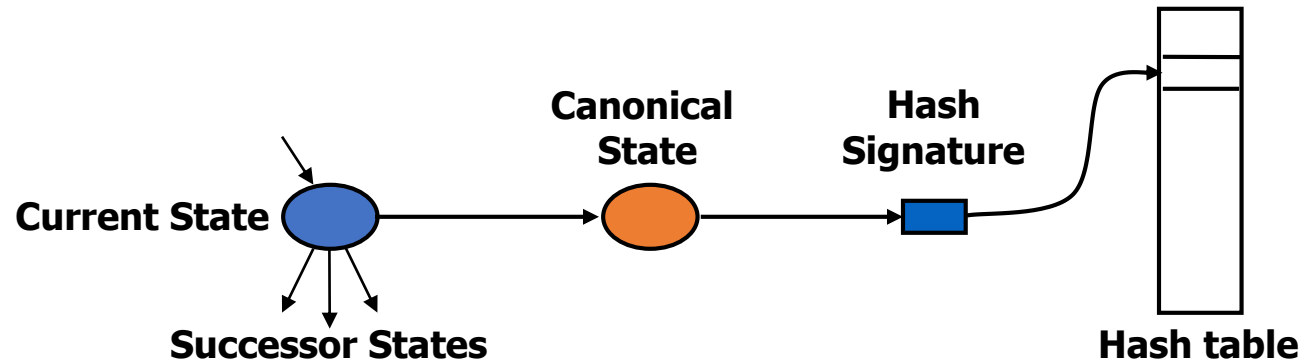
- Typically a state transition involves changing very small state
 - Updating a local variable in the stack
 - Creating a new object on the heap
- Instead of storing the entire state each time in hash table ...
- Store the delta (change) from the previous state in hash table

State Space Reduction Techniques

- State collapsing
- **Heuristic state approximation**
- Hash compaction
- Heap canonicalization
- Symbolic execution

Heuristic state approximation

- Explore one out of a (large) set of equivalent states
- Canonicalize (unify) states before hashing



- Example: suppose an int value has two equivalence classes
 - When hashing to check for match with an already visited state, Unify all values in equivalence class to one chosen value
 - Leads to a drastic reduction in visited states
 - Can also lead to missed defects – **unsound**

State Space Reduction Techniques

- State collapsing
- Heuristic state approximation
- **Hash compaction**
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Hash compaction

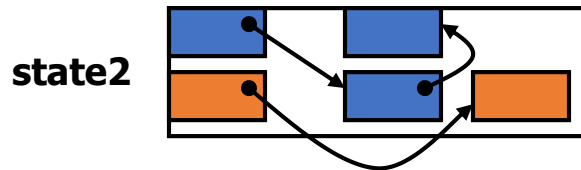
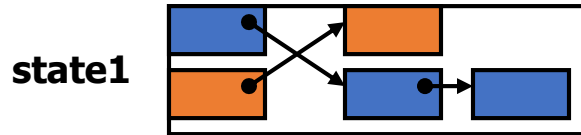
- Only store hash of state in the hash table
 - Do not store the actual state
 - A state match is determined solely by an equality check on the hash
- Might miss defects due to hash collisions – **unsound**
 - Two states that are different may be stored as the same hash
 - Means some states will not be visited as a result
- But orders of magnitude memory savings
 - Can compact 100 kilobyte state to 4-8 bytes!

State Space Reduction Techniques

- State collapsing
- Heuristic state approximation
- Hash compaction
- **Heap canonicalization**
- Symbolic execution

Heap canonicalization

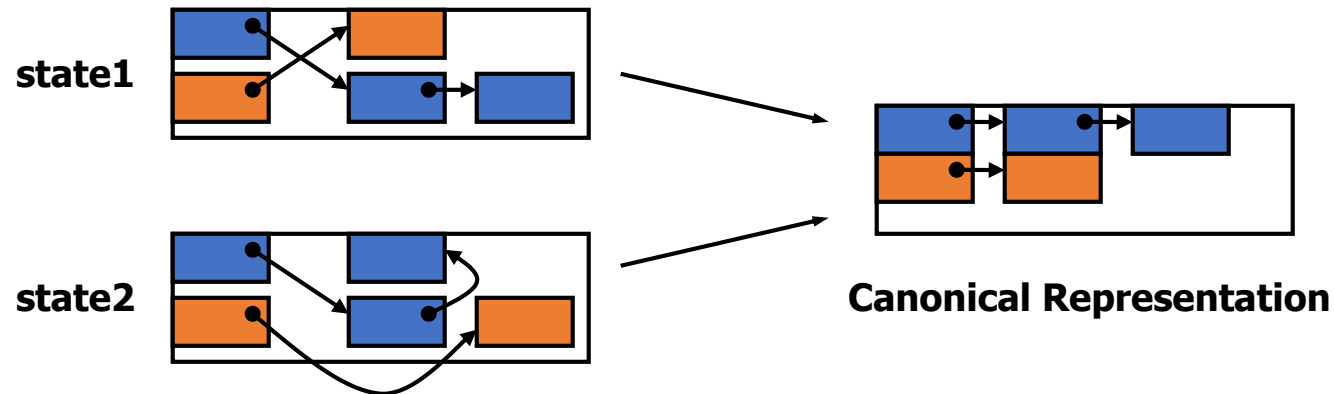
- Problem: two logically equivalent program states appear different because of differences in heap layout
- Example:



- Are the two states logically different?
 - No! But appears different due to different reference pointer values.

Heap canonicalization

- Solution: Canonicalize heap to unify layout
- Example:



- Canonical layout can be found by doing a fixed traversal of heap
 - DFS: Depth first search, or BFS: Breadth first search
- Note: can do it incrementally on each heap modification w/o full traversal

State Space Reduction Techniques

- State collapsing
- Heuristic state approximation
- Hash compaction
- Heap canonicalization
- Symbolic execution

To be continued ...