CS1632:
Static Analysis, Part 2

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Kinds of Static Tests

- Code review / walk-through
- Compiling
- Code coverage
- 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!?

… with some caveats ☺

Methods of Formal Verification

- Theorem Proving
  - Deducing postcondition from precondition through math

Caveat

- Model Checking
  - Given a finite state model of a system, exhaustively checking all the states to see if model meets a given specification

Caveat

Theorem Proving

Deducing postconditions from preconditions through math

Hoare Logic Theorem Proving

- Hoare Logic: Proves a Hoare Triplet through mathematical deduction
- Hoare Triplet: {Precondition} Program {Postcondition}
  - Meaning: Given Precondition and Program, Postcondition is always true

- Examples of Hoare Triplets (x is a variable, A and B are constants):
  - { True } x = A { x == A }
  - { x == A } x = x + B { x == A + B }
  - { x == A } if (x < 0) then x = -x { x == |A| }
  - { True } if (x < 0) then x = -x { x >= 0 }

Proof is done by composing Hoare Logic Triplets

- Suppose we wanted to prove the following assertion passes:
  x = -5;
  x = x + 3;
  if (x < 0) then x = -x;
  assertEquals(2, x);   // prove this passes
- Composition of Hoare Logic Triplets:
  1. { True } x = -5 { x == -5 } and { x == -5 } x = x + 3 { x == -5 + 3 == -2 }
     → { True } x = -5; x = x + 3 { x == -2 }
  2. { True } x = -5; x = x + 3 { x == -2 } and { x == -2 } if (x < 0) then x = -x { x == |-2| == 2 }
     → { True } x = -5; x = x + 3; if (x < 0) then x = -x { x == 2 } → `Proof Complete!`

- Proof can be generated by human or automated theorem prover

Theorem Proving Advantages

- Can prove large programs with many (infinite) states
  - Model checker needs to visit each state to verify property is true
  - E.g. to prove { True } if (x < 0) then x = -x { x >= 0 }
    → Model checker needs to verify postconditions by visiting all values of x

- 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
  - Automated theorem provers often needs human assistance
    (e.g. They have trouble reasoning about data structures like lists, trees, etc.)
  - Highly skilled people with formal methods training is needed

- Automated proofs can be obscenely long
  - In one report by Motorola, a proof was 25 MB long (more than 100 pages)
  - Hard for humans to comprehend and double check the proof

Industry Reception

- Used only in niche markets where correctness is paramount
  - Mission critical systems, cryptography libraries, OS kernels
  - Proof for seL4 OS microkernel: https://github.com/seL4/l4v

- 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

- Does implementation satisfy specification ?
- Implementation is also called a system model.
    - System model can be just your source code
    - Or some abstract model derived from source code
- Specification is also called a system property.
    - The same “property” in property-based testing

Examples of System Properties

- Memory related properties
  - No out of bounds array accesses
  - No null references
  - No leaks, double-free, access after free (in C/C++)
- Thread related properties
  - No dataraces when threads access shared data
- User assertions (invariants)
  - Embedded in source code or part of property-based unit test

Comparison with Stochastic Testing

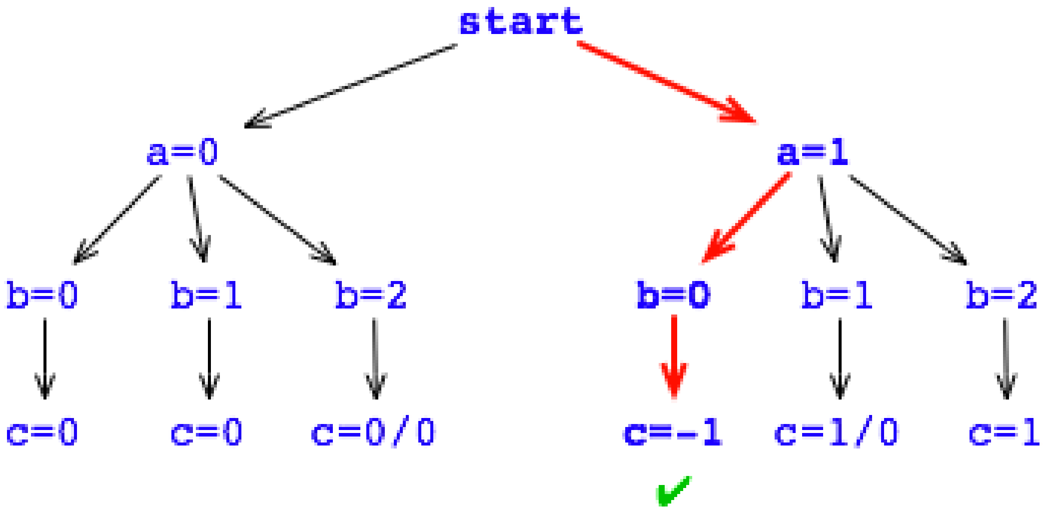
- Similarity
  - Model checking also tests a property, not an output value
- Difference
  - With stochastic testing, we tested (a few) randomized input values
  - With model checking, all states are checked *exhaustively*

Stochastic Testing (on a Single Trial)

Given this code:

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

If unlucky and not all paths are covered after all trials,
bug may never be found!



① Random random = new Random()

② int a = random.nextInt(2)

③ int b = random.nextInt(3)

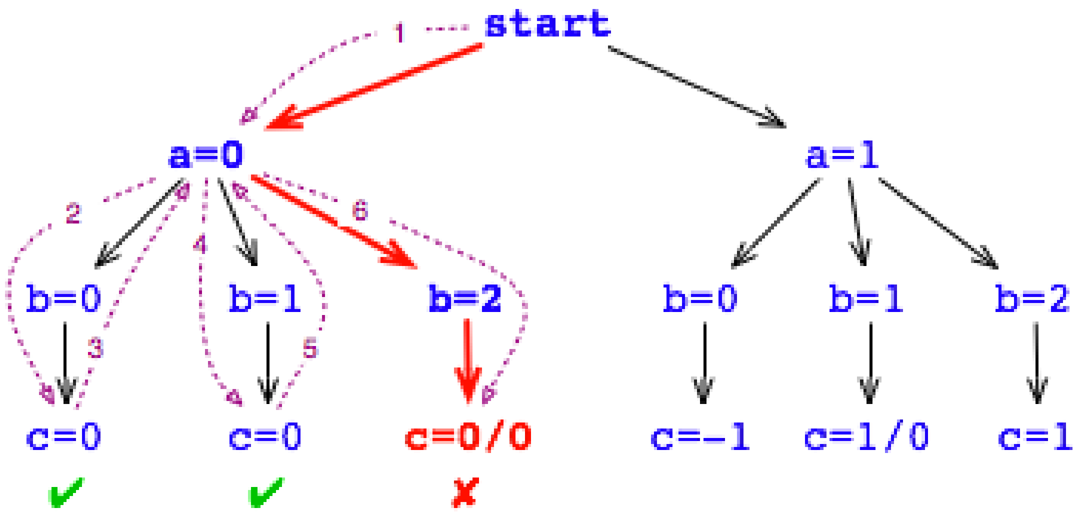
④ int c = a/(b+a -2)

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!



① `Random random = new Random()`

② `int a = random.nextInt(2)`

③ `int b = random.nextInt(3)`

④ `int c = a/(b+a -2)`

State Explosion Problem

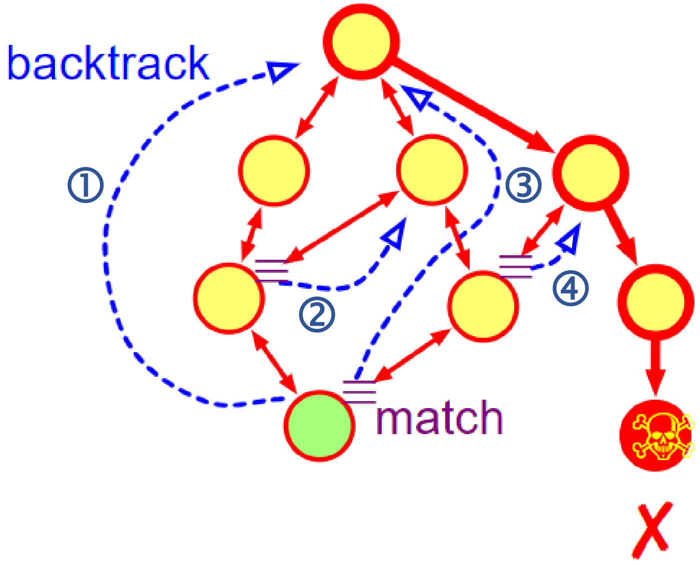
- Non-trivial programs have many more states in their Finite State Machines
  - May run into memory limitations (can’t contain entire state graph)
  - May run into time limitations (can’t explore entire graph within allotted time)

  → This is called the **State Explosion Problem**

- Single reason preventing wide adoption of model checking

- **State matching & backtracking** alleviates the problem but not all

State Exploration with Matching & Backtracking



Circles: Program states
Arrows: State transitions

- State divergence happens when there is a *choice*
  - Value from random number generation or user input
  - Choice of thread to run among multiple threads
- **Match**
  - When next state matches a previously visited state
  - Backtrack to not repeat work
- **Backtrack**
  - On reaching terminal state or when there is a match
  - Go to closest previous state with unexplored transition

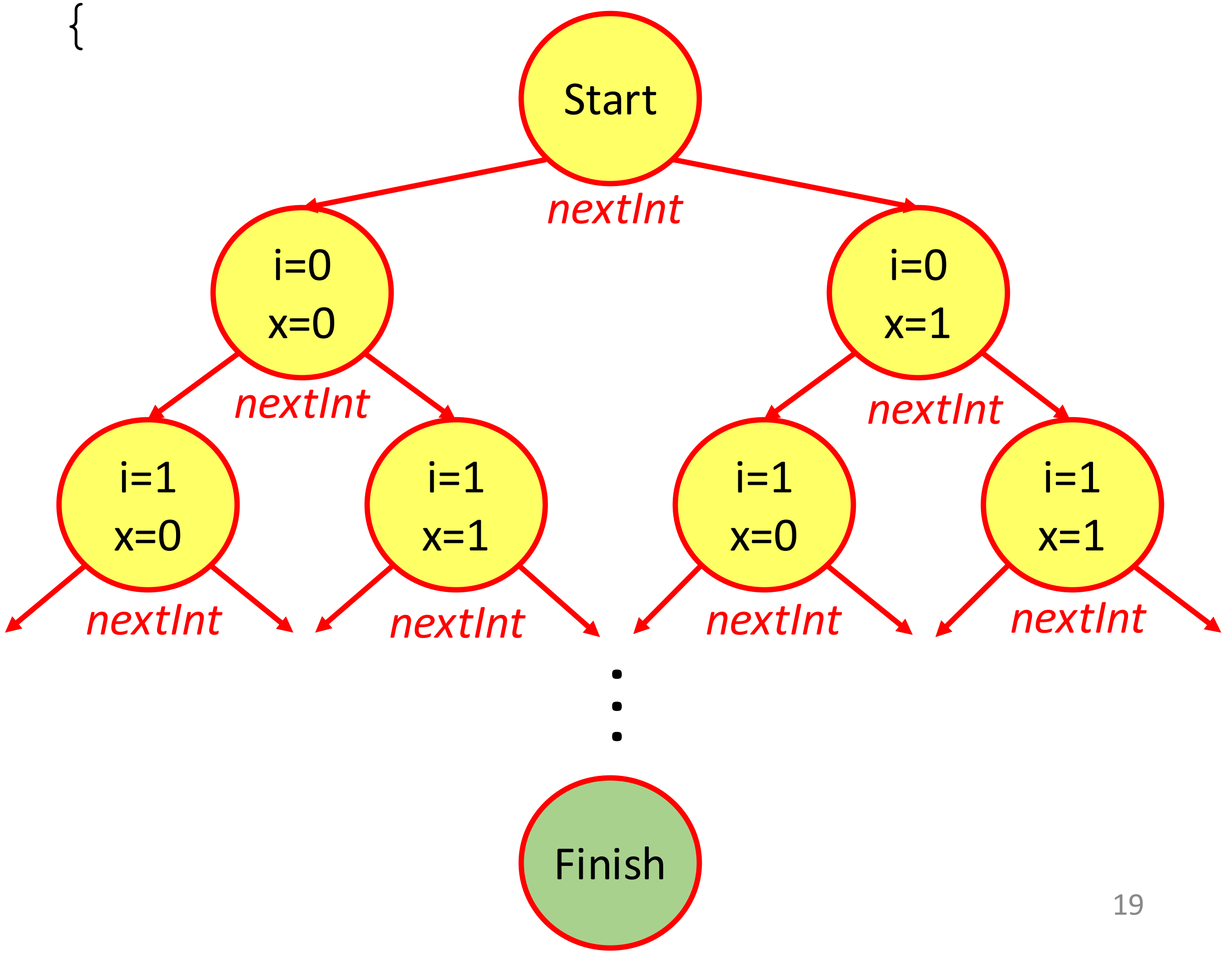
→ Ensures **each unique state is visited only once**

Matching & Backtracking: Example 1

- Given below code:

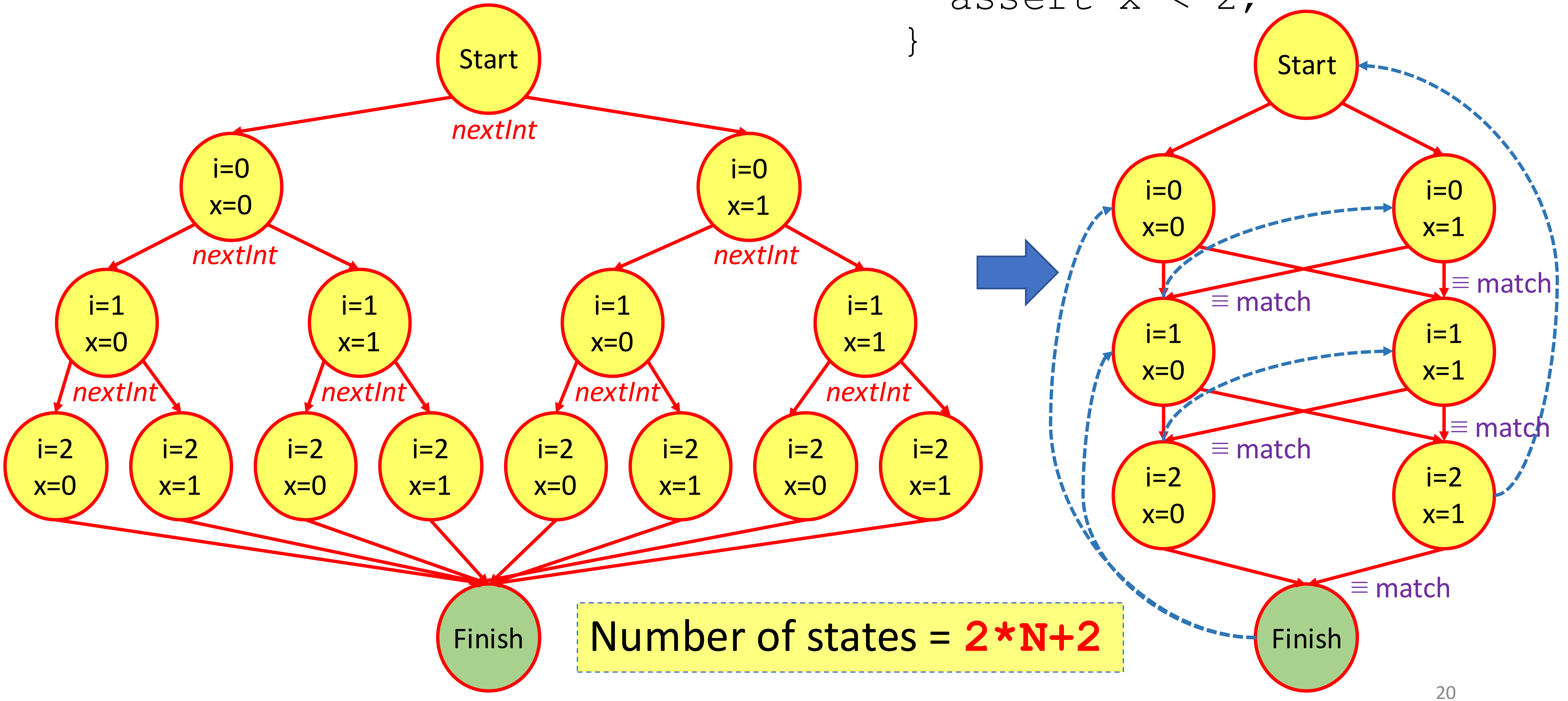
```
for(int i = 0; i < N; i++) {
   x = rand.nextInt(2);
   assert x < 2;
}
```

- Potential number of states = 2^{N+1}



Matching & Backtracking on

```
for(int i = 0; i < 3; i++) {
  x = rand.nextInt(2);
  assert x < 2;
}
```

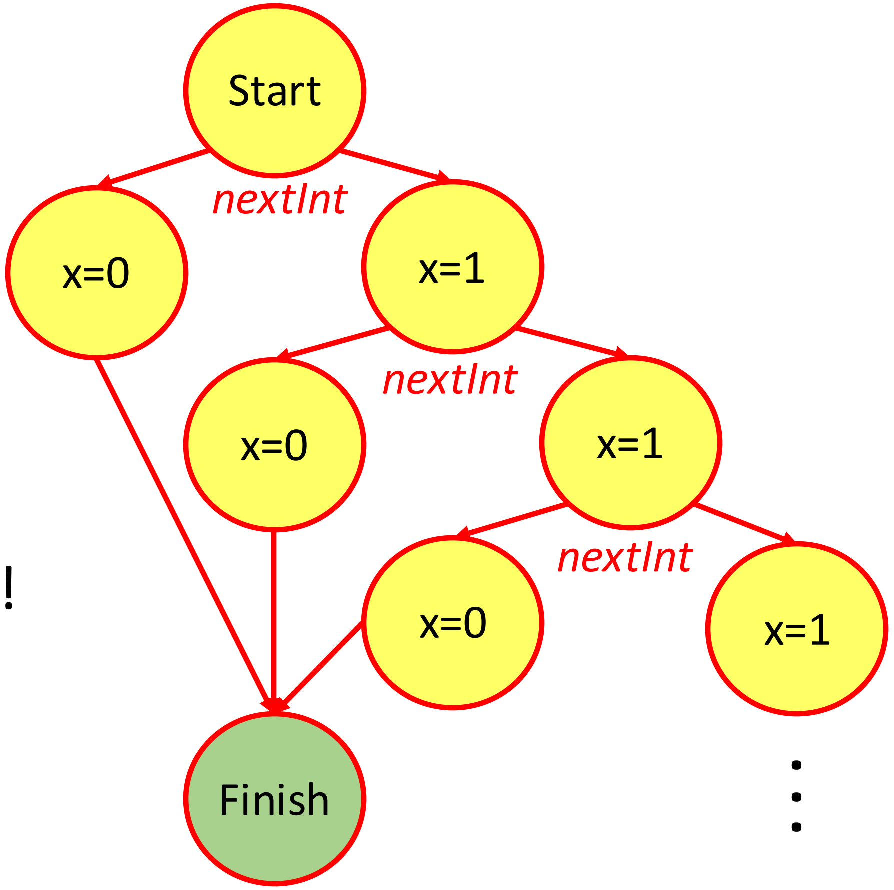


Number of states = **2*N+2**

Matching & Backtracking: Example 2

- Given below code:

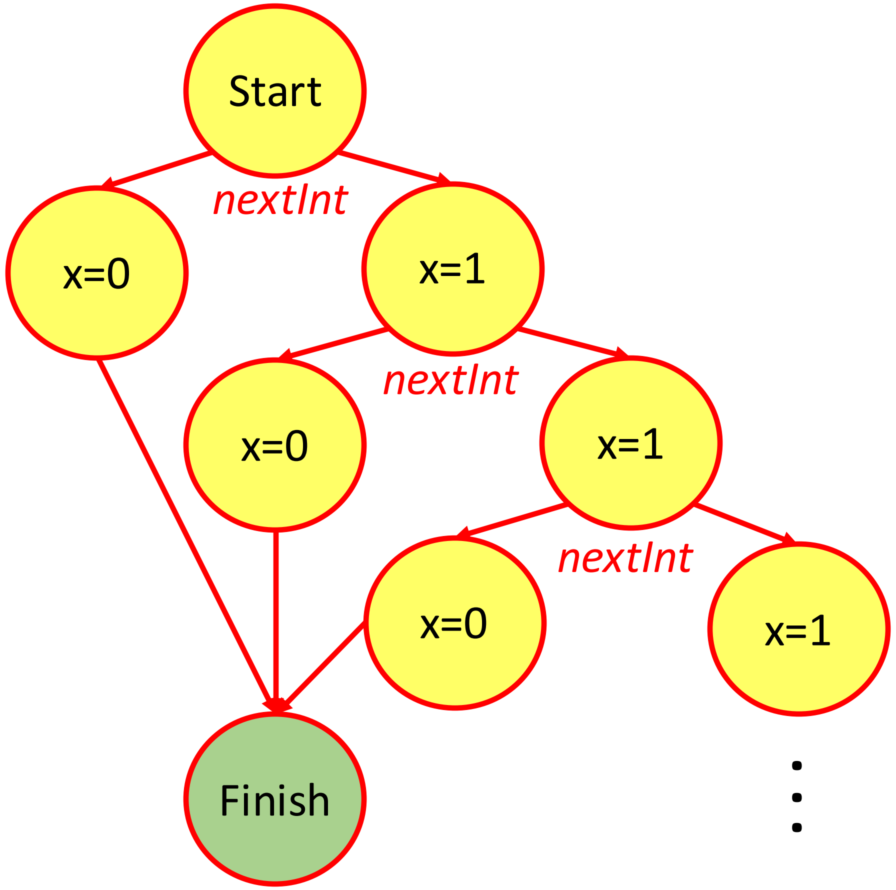
```
while(true) {
   x = rand.nextInt(2);
   if(x == 0) break;
   assert x < 2;
}
```

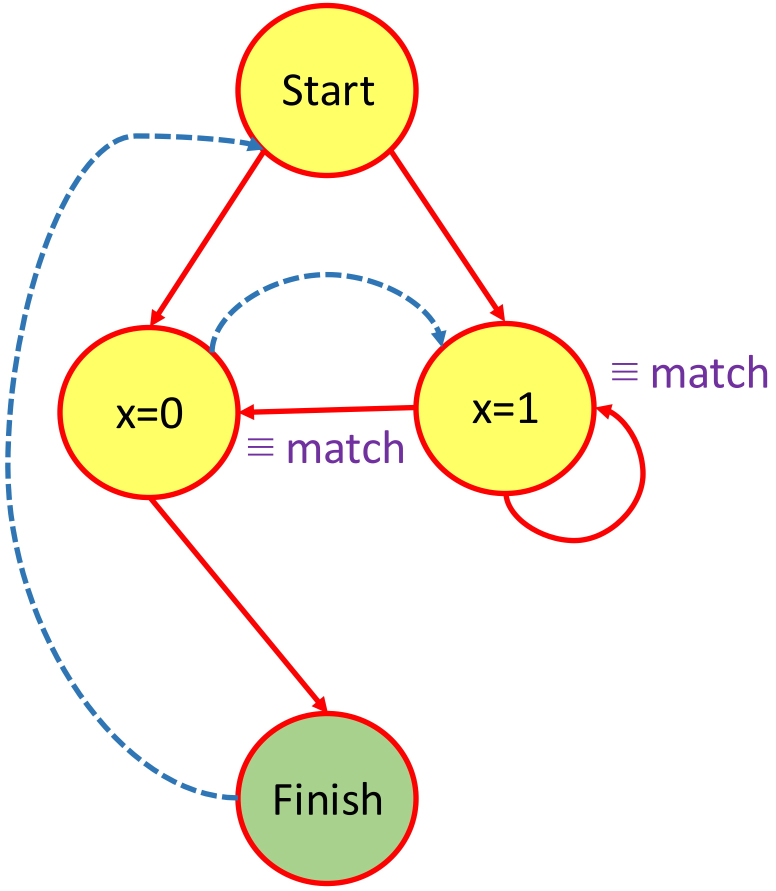


- Model checker can potentially go on forever!
  - Will keep creating states to the right

Match & Backtrack on

```
while(true) {
   x = rand.nextInt(2);
   if(x == 0) break;
   assert x < 2;
}
```





Number of states = **4**

Efficient State Exploration with Backtracking

```
Hashtable states_seen;
Stack pending;

pending.push(initial_state);
while(!pending.empty()){
      current = pending.pop();
      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.push(successor);
      }
}
```

State Space Explosion Sometimes is Unavoidable

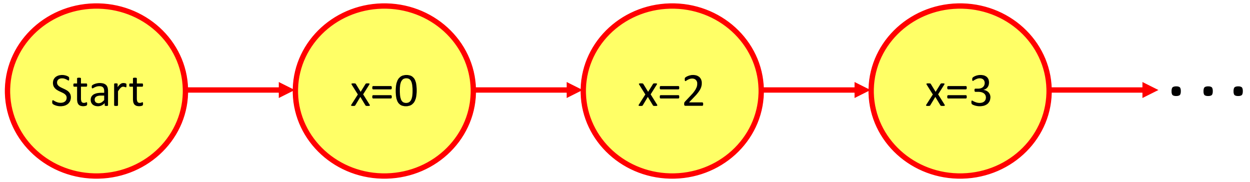
- Even with state matching, sometimes state space explodes

- May have to filter out part of program state that causes explosion
  - Human has to tag variables or objects as filtered
  - May result in parts of program state that are not verified
  - But these parts are typically not the parts that require rigorous verification (Involve event counters, statistics, logs, etc.)

State Explosion Even with State Matching

- Given below code:

```
x = 0;
while(true) {
  x = x + 1;
  assert x > 0;
}
```



- The value of x keeps incrementing at every iteration, creating a new state
  - Results in state explosion, making it impossible to model check!
  - Variables like these are typically stat counters, which can be filtered out with minimal loss

Limiting State Creation Using @FilterField

```
public class WebServer {
  // For statistics gathering purposes
  @FilterField int pageCounter;

  public void sendPage(String url) {
    pageCounter++;
    // Do the actual processing
  }
}
```

- `pageCounter` puts `WebServer` in a new state every time `sendPage` is called
  → Means state cannot be matched, even if state remains the same otherwise
  → Leads to a lot of unnecessary state creation
- `@FilterField` says, ignore `pageCounter` for the purposes of state matching

Java Path Finder (JPF)

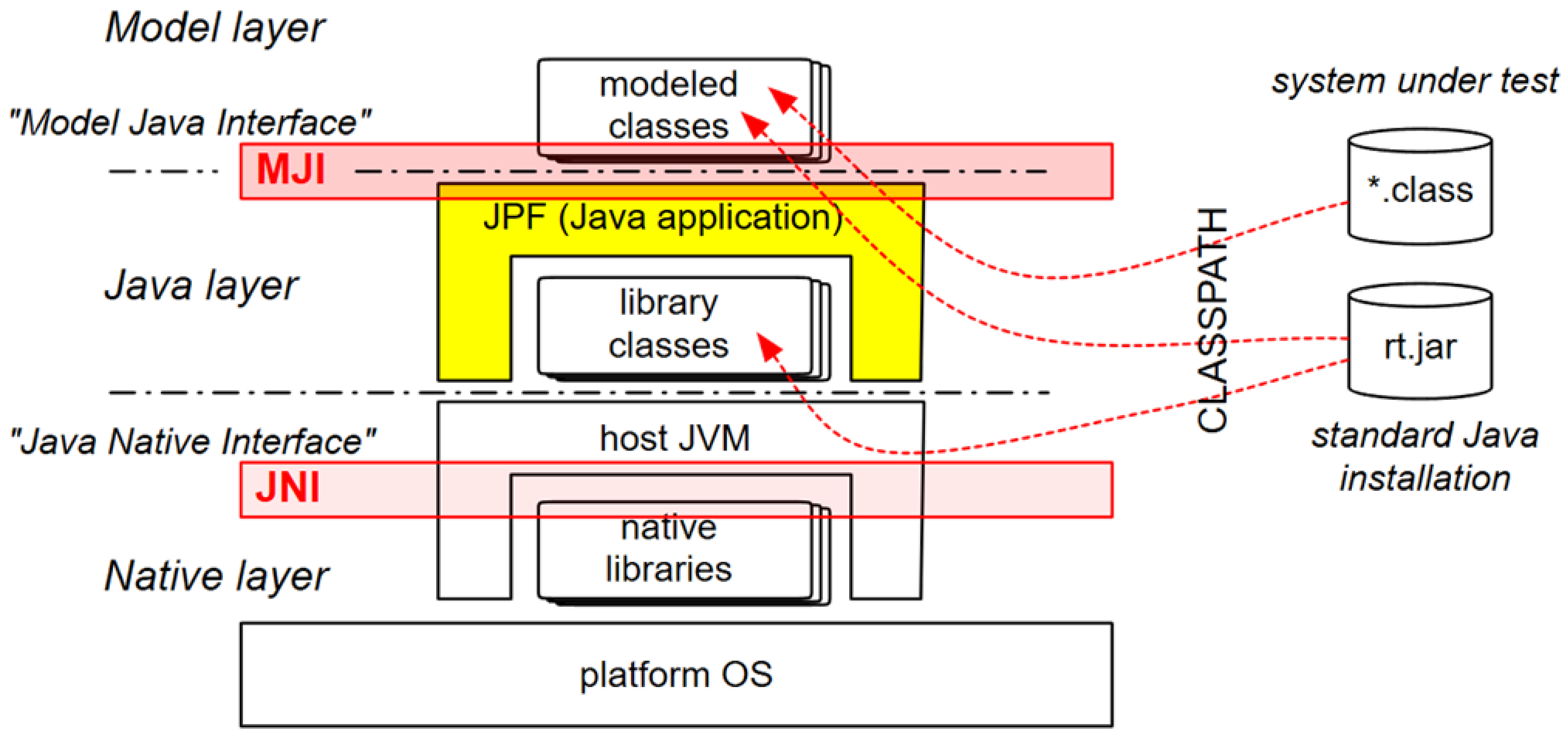
A Model Checker for Java

Java Path Finder (JPF)

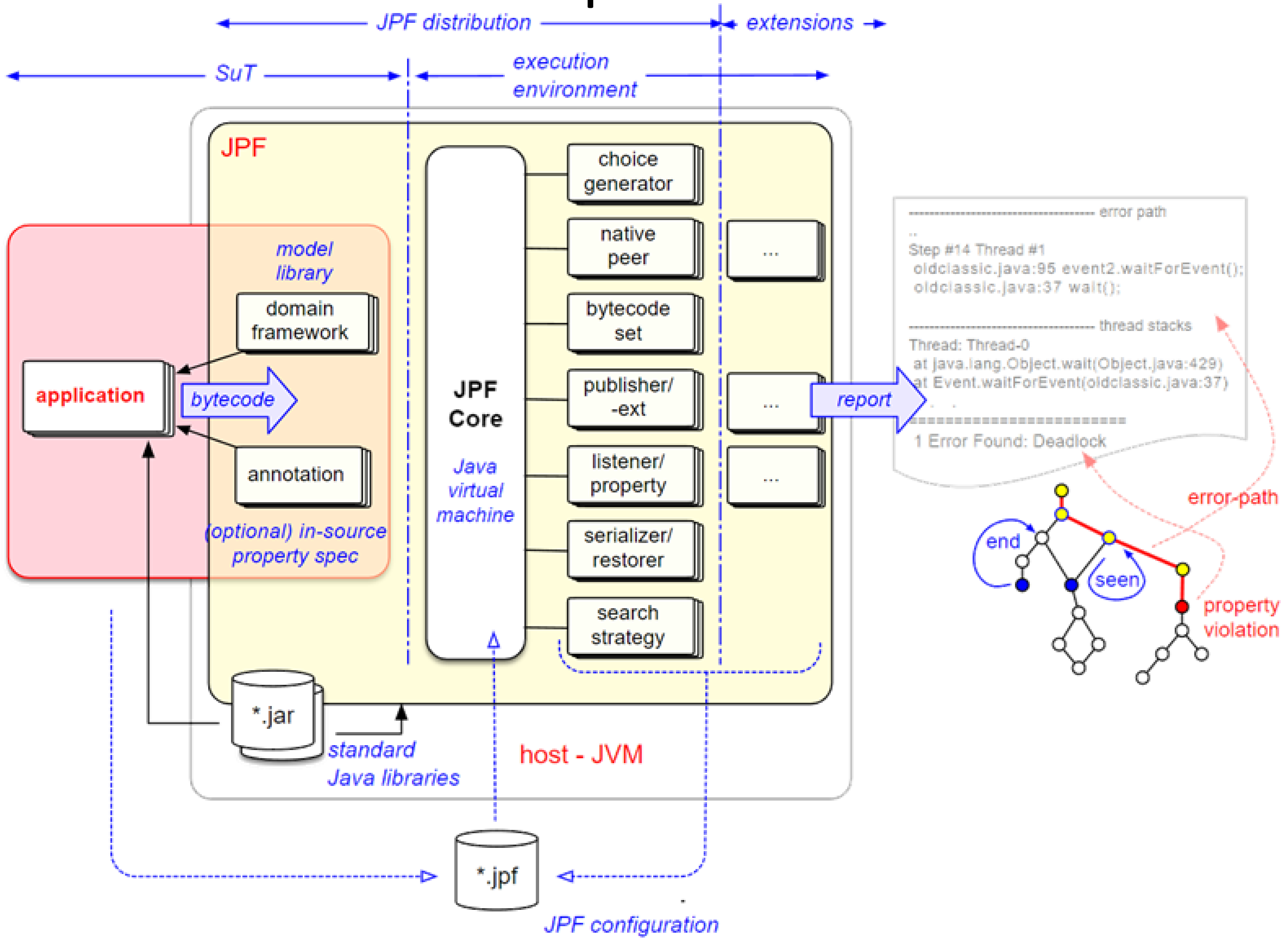
- A model checker for Java: Uses all the principles we learned
  - Called Path Finder because it explores all paths in finite state machine
  - Concrete model checker: system model is the Java Virtual Machine
    → No need to translate source code into abstract model

- Developed and maintained by NASA
  - To model check code for their space missions
  - Open Source / Apache License Version 2
  - Released 2010, still actively maintained and extended

App executes on top of Java Path Finder JVM



Java Path Finder is a special Java Virtual Machine



Java Path Finder: Example Configuration File

```
# Target class main method to run.  In this case, we are invoking JUnit through the TestRunner.
target = edu.pitt.cs.Rand
target.args =

# If set to true, enumerates all possible values returned by Random.nextInt.
# If set to false, the original Random.nextInt is called to generate an actual random number.
cg.enumerate_random = true

# On property violation, print the error, the choice trace, and the Java stack snapshot
report.console.property_violation=error,trace,snapshot

# If true, prints program output as JPF traverses all possible paths
vm.tree_output = true
```

Java Path Finder: Example Report

JavaPathfinder core system v8.0 - (C) 2005-2014 United States Government. All rights reserved.

====================================== system under test

TestRunner.main() **Main method you are testing**

====================================== search started: 3/27/20 12:38 AM

PROGRAM OUTPUT **Output of your program if any**

====================================== results

no errors detected **Errors will be listed if there are exceptions or assertion failures**

====================================== statistics

elapsed time: 00:00:06 **Time elapsed for testing in hours:mins:seconds**

states: new=4155,visited=3529,backtracked=7684,end=467

…

States created while model checking

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Verify API: Enumerating Input Values

- Suppose you want to prove the following main method correct:

```
public static void main(String[] args) {
   int x = Integer.parseInt(args[0]);
   int y = Integer.parseInt(args[1]);
   int diff = x - y;
   if (x > y) assert diff > 0;
   if (x < y) assert diff < 0;
   System.out.println(x + " - " + y + " = " + diff);
   return;
}
```

- And you want to prove it correct for a set of command line arguments

Verify API: Enumerating Input Values

- Verify meaning: verify program for the specified set of input values

```
public static void main(String[] args) {
  int x = Verify.getInt(3, 5);
  int y = Verify.getIntFromList(4, 6);
  int diff = x - y;
  if (x > y) assert diff > 0;
  if (x < y) assert diff < 0;
  System.out.println(x + " - " + y + " = " + diff);
  return;
}
```

- In terms of semantics, very similar to Random value enumeration

Verify API: Java Path Finder Report

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=== system under test

JPFTester.main()

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3 - 4 = -1

3 - 6 = -3

4 - 4 = 0

4 - 6 = -2

5 - 4 = 1

5 - 6 = -1

Output of:

```
x = Verify.getInt(3, 5)
y = Verify.getIntFromList(4, 6)
```

=== results

no errors detected

…

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JUnit Testing with Java Path Finder

JPF is invoked on-demand by JUnit

- All JUnit tests are executed on the host Java virtual machine
  - All @Test, @Before, @After methods executed on the host JVM
- For @Test methods that you want to run using JPF, call **`verifyNoPropertyViolation()`** at beginning of method

- Semantics of **`verifyNoPropertyViolation()`** :
  - Creates a new JPF virtual machine that starts executing the @Test method
  - Results in two virtual machines executing the @Test method
    - **Host** virtual machine: returns **false** on verifyNoPropertyViolation() call
    - **JPF** virtual machine: returns **true** on verifyNoPropertyViolation() call

Example JUnit Test using JPF

```
public class ArithmeticTest {
  private int x = 0;

  public void setUp() {
    x = Verify.getInt(-5, 5);
  }
  @Test public void testSquare() {
    if (verifyNoPropertyViolation() == false) {
      // This is the host virtual machine so return immediately.
      return;

    }
    setUp();  // Call setUp() on the JPF virtual machine.
    int y = x * x;
    assertTrue(y > 0);
  }
  …
}
```

Pitfall: JUnit Test using JPF

```
public class ArithmeticTest {
  private int x = 0;

  @Before public void setUp() {
    x = Verify.getInt(-5, 5);
  }

  @Test public void testSquare() {
    if (verifyNoPropertyViolation() == false) {
      // This is the host virtual machine so return immediately.
      return;

    }
    // Bug! @Before executed on host, not on JPF virtual machine!
    int y = x * x;
    assertTrue(y > 0);
  }
  …
}
```

Backup

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

$$x \in \text{Variable}$$

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

- 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 (most)* programs it can be solved

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

Concrete and Abstract Model Checking

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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

Language and Concrete Model Checking

- Not many programming languages have a dedicated model checker

- 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

State Space Reduction Techniques

- State space can be infinite (or very large)
  - Try exploring as many behaviors as possible (likely you can’t explore all)
  - Focus on precision (finding defects accurately)

- Techniques to reduce memory consumption due to state space
  - State collapsing
  - Heuristic state approximation
  - Hash compaction
  - Heap canonicalization
  - Symbolic execution

State Space Reduction Techniques

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

State collapsing

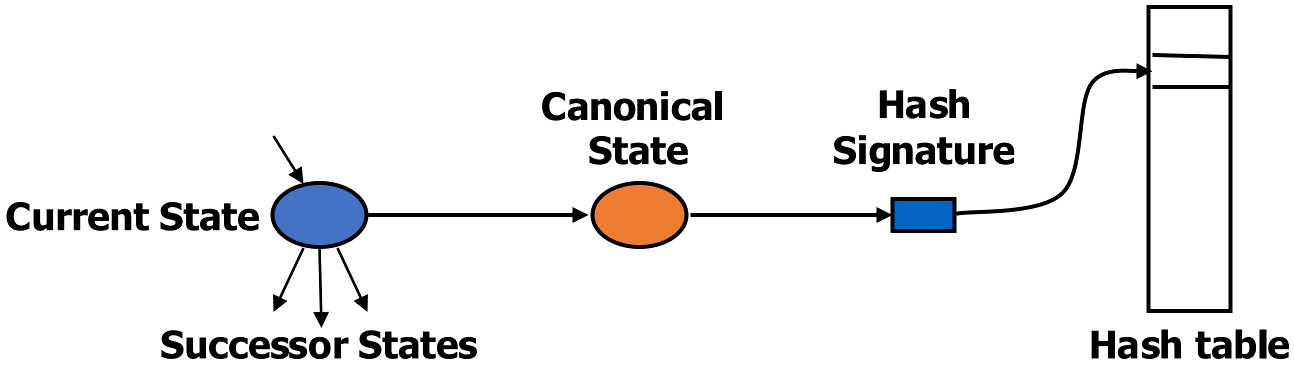
- Typically a state transition involves changing very small state
  - Updating a local variable in the stack
  - Creating a new object on the heap
- Instead of storing the entire state each time in hash table …
- Store the delta (change) from the previous state in hash table

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
- Heap canonicalization
- Symbolic execution

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

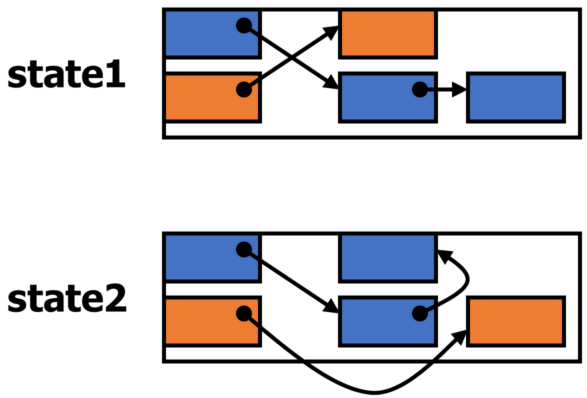
- But orders of magnitude memory savings
  - Can compact 100 kilobyte state to 4-8 bytes!

State Space Reduction Techniques

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

Heap canonicalization

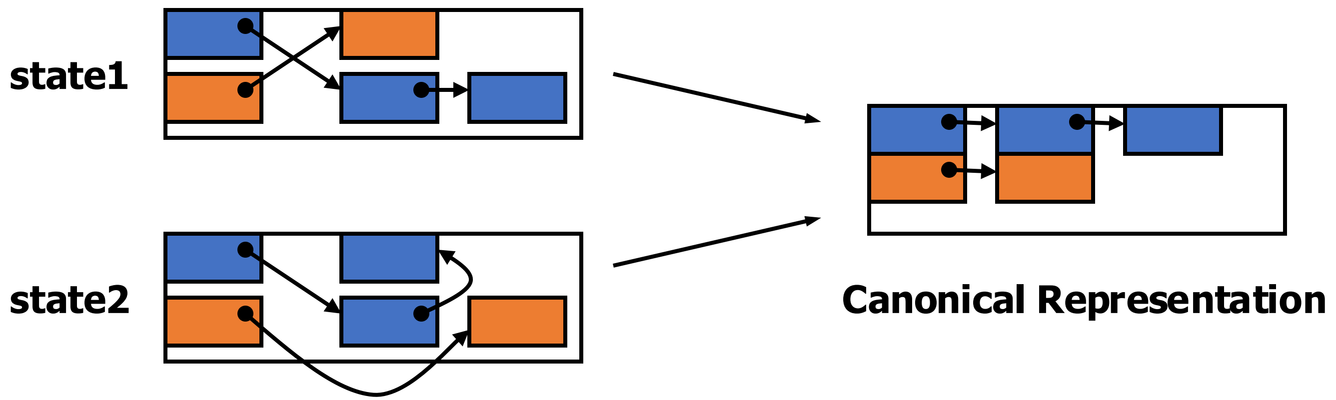
- Problem: two logically equivalent program states appear different because of differences in heap layout
- Example:



- 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 …