CS1632, Lecture 16: Static Analysis, Part 2

Wonsun Ahn

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!?

Methods of Formal Verification

- Theorem Proving
  - Deducing postcondition from precondition through math

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

Theorem Proving

Deducing postcondition from precondition through math

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 { Infinite loop } ← No such triple!

Hoare Logic Syntax

English	Formal
false	$\bot$
true	$\top$
not p	$\neg p$
p and q	$p \wedge q$
p or q	$p \vee q$
p implies q	$p \Rightarrow q$
p iff q	$p \Leftrightarrow q$
for all x, p	$\forall x. p$
there exists x such that p	$\exists x. p$

- 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 { Infinite loop }
  - 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

$$I \models S$$

"implementation"
(system model)

"specification"
(system property)

"satisfies", "implements", "refines"
(satisfaction relation)

Examples of System Properties

- Assertions (invariants)
  - Embedded in source code or part of property-based unit test
- 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
- Security related properties
  - No write of private data to insecure public channels

Comparison with Property-Based Testing

- Similarity
  - Model checking also tests a property, not an output value

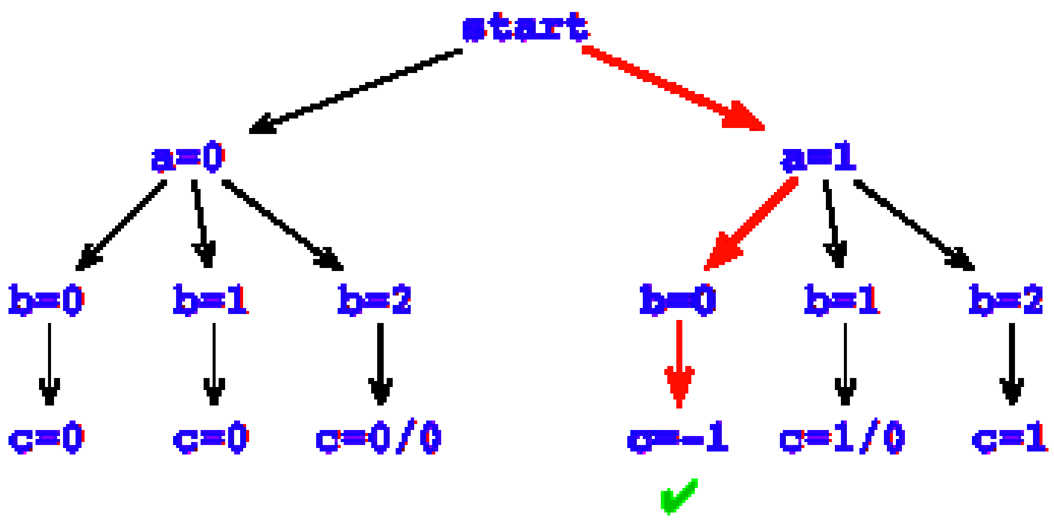
- Difference
  - With stochastic testing, we tested (a few) randomized input values
  - With model checking, all states are checked *exhaustively*

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)

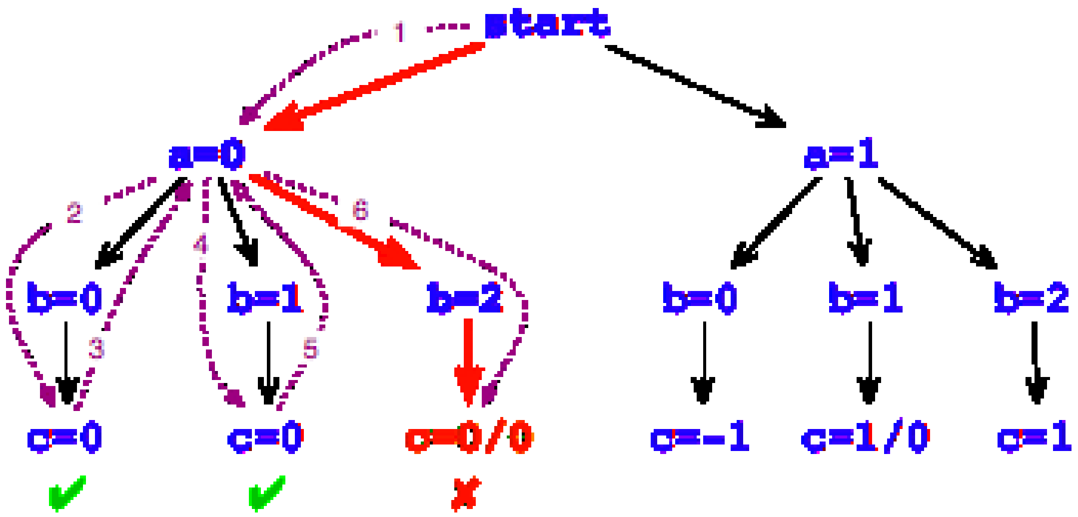
④ int c = a/(b+a -2)

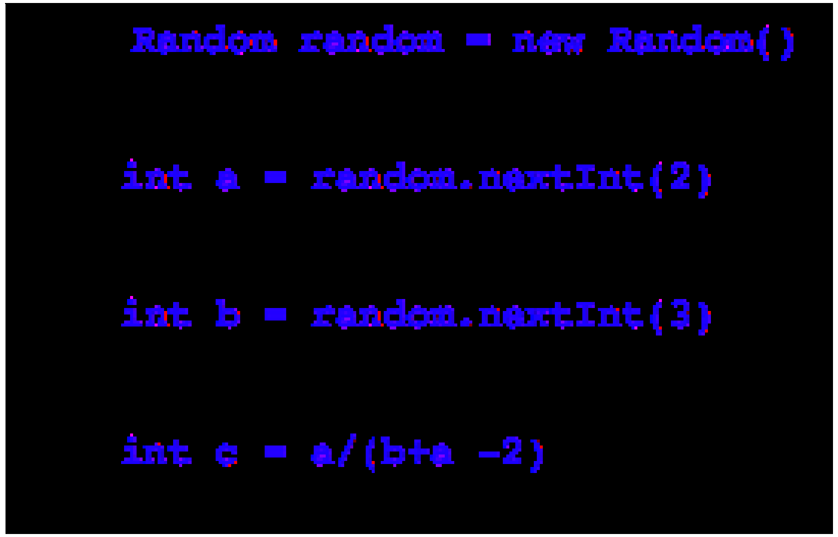
Model Checking

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!





State Explosion Problem

- Did you notice? You may end up with *a lot* of states.

- Single reason preventing wide adoption of model checking
  - May run into memory limitations (can’t contain entire state graph)
  - May run into time limitations (can’t explore entire graph within allotted time)
  - Especially a big problem for sizable programs (> 100,000 lines of code)

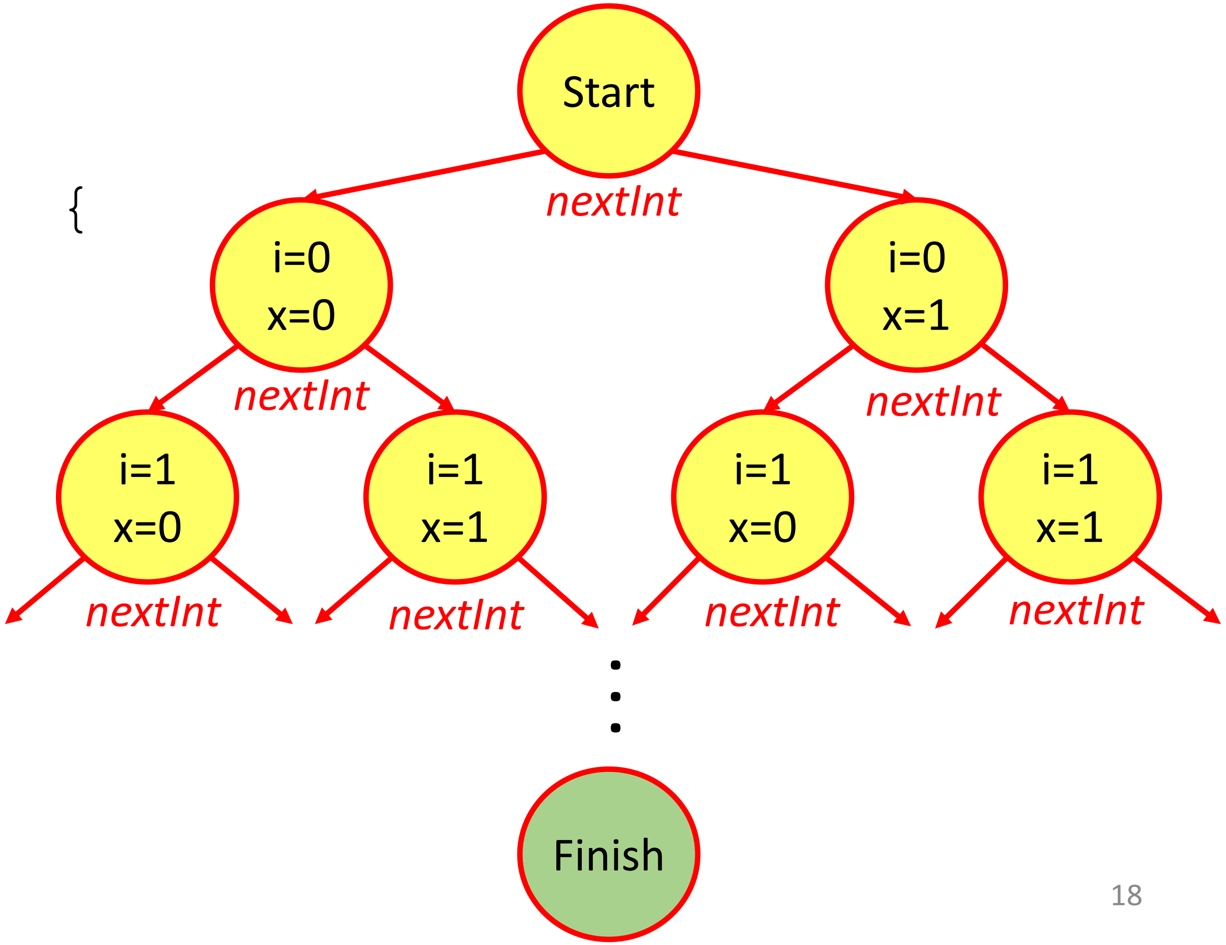
State Explosion Problem: Example 1

- Number of states explodes exponentially with each call to `random.nextInt`

- Given below code:

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

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



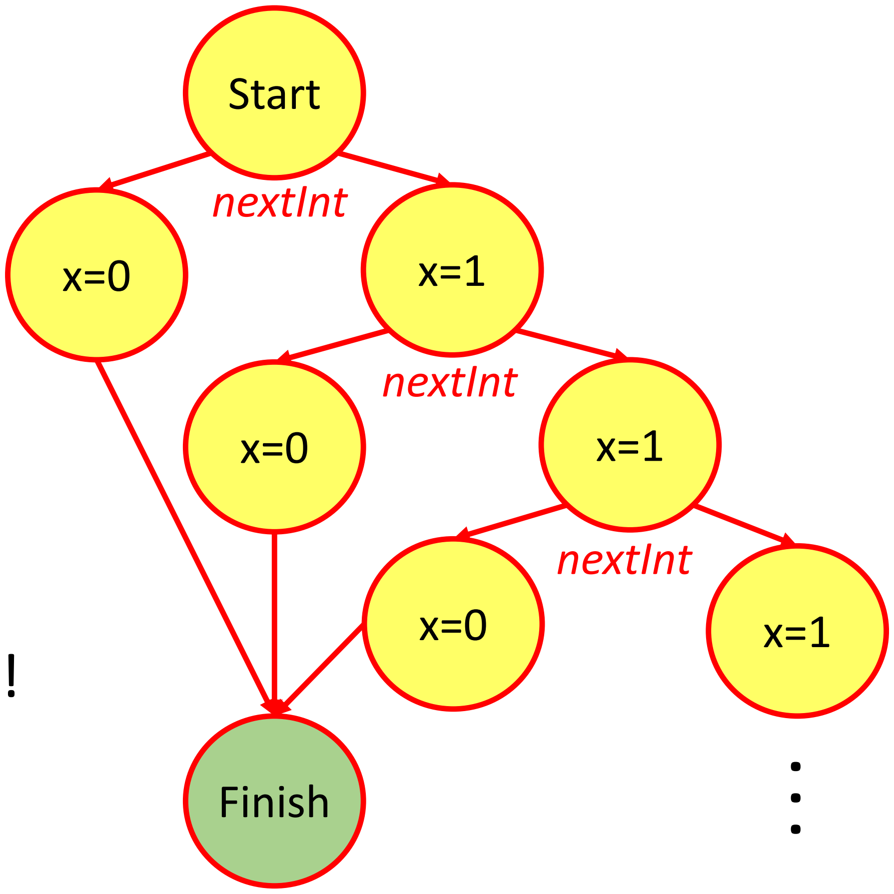
State Explosion Problem: Example 2

- You might even end up with an infinite number of states!

- 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



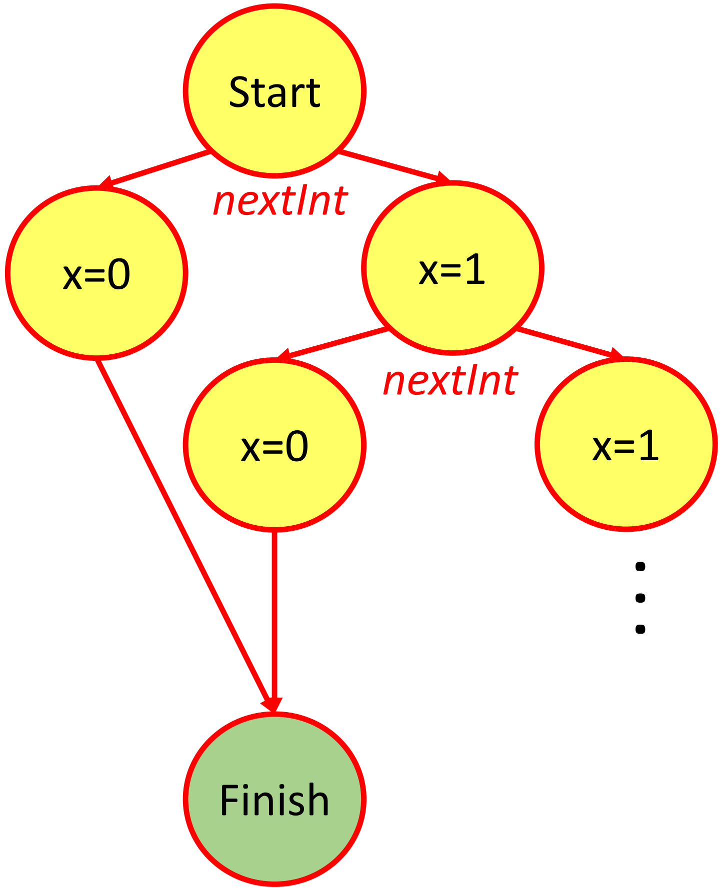
Solution: Match & Backtrack

- If you were paying attention, you might have noticed …

- Sometimes we encounter identical states already visited:
```
for(int i = 0; i < N; i++) {
   x = rand.nextInt(2);
}
```
  → If you do, do not create a new state, backtrack!

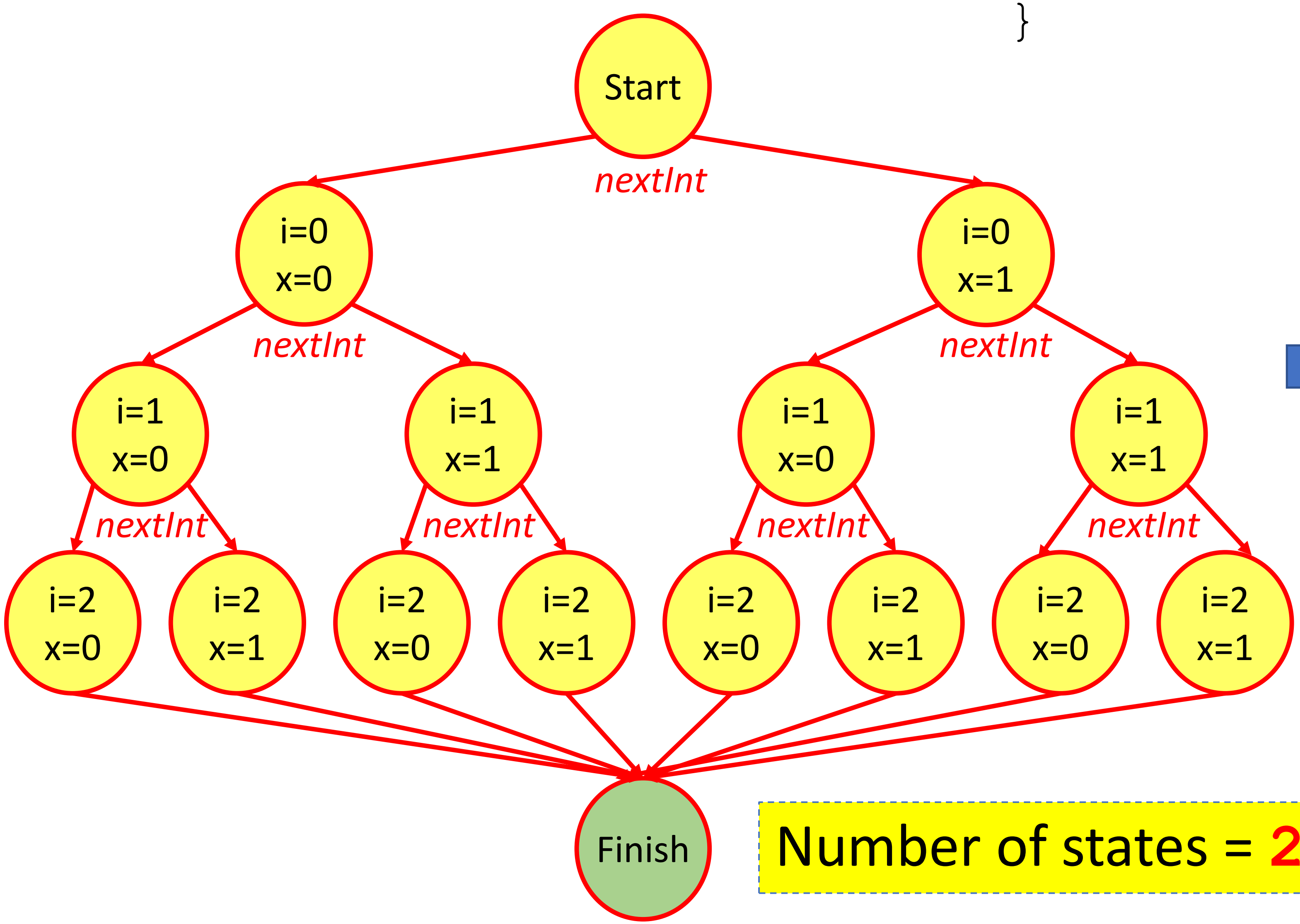
- Backtrack: going to closest previous state with unexplored transition
  - When next state matches a previously visited state
  - When you reach the finish state

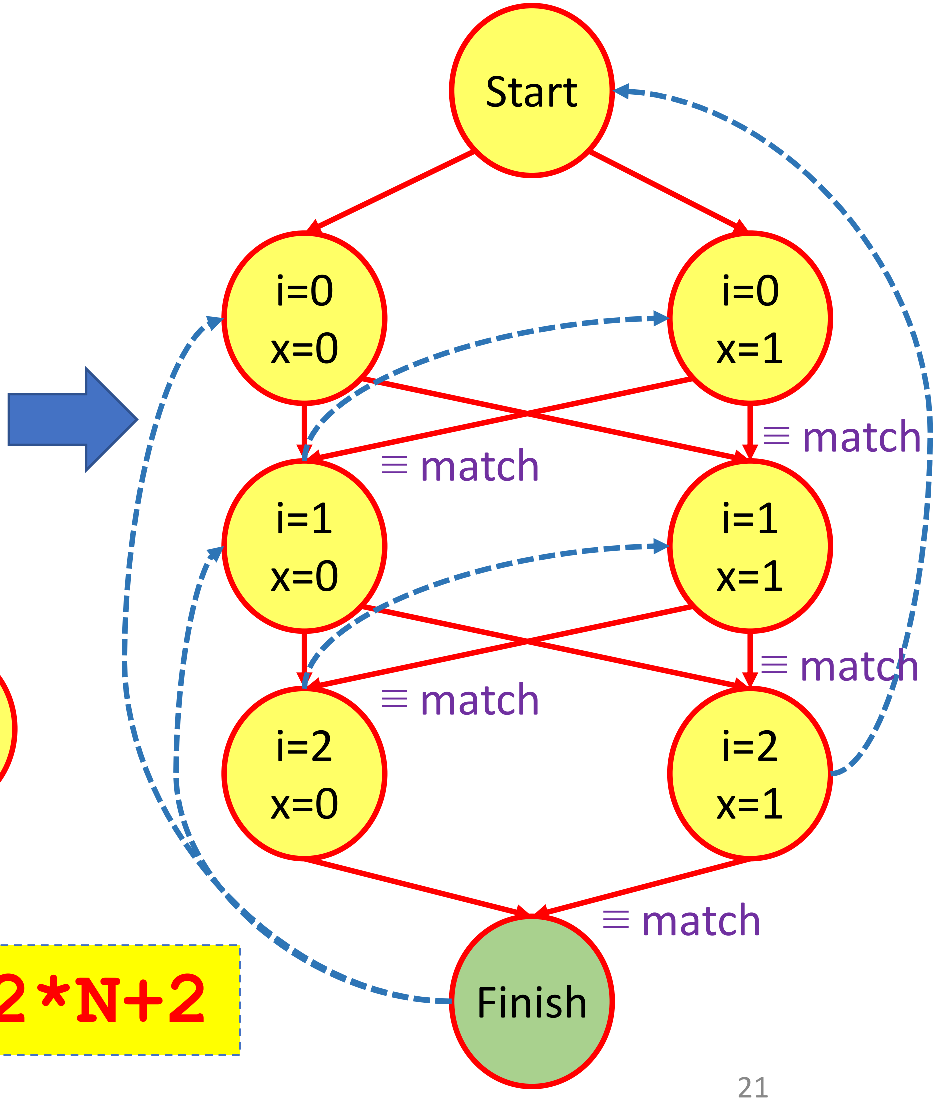
- Let's assume we visit states in Depth First Search (DFS) order



Match & Backtrack on

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

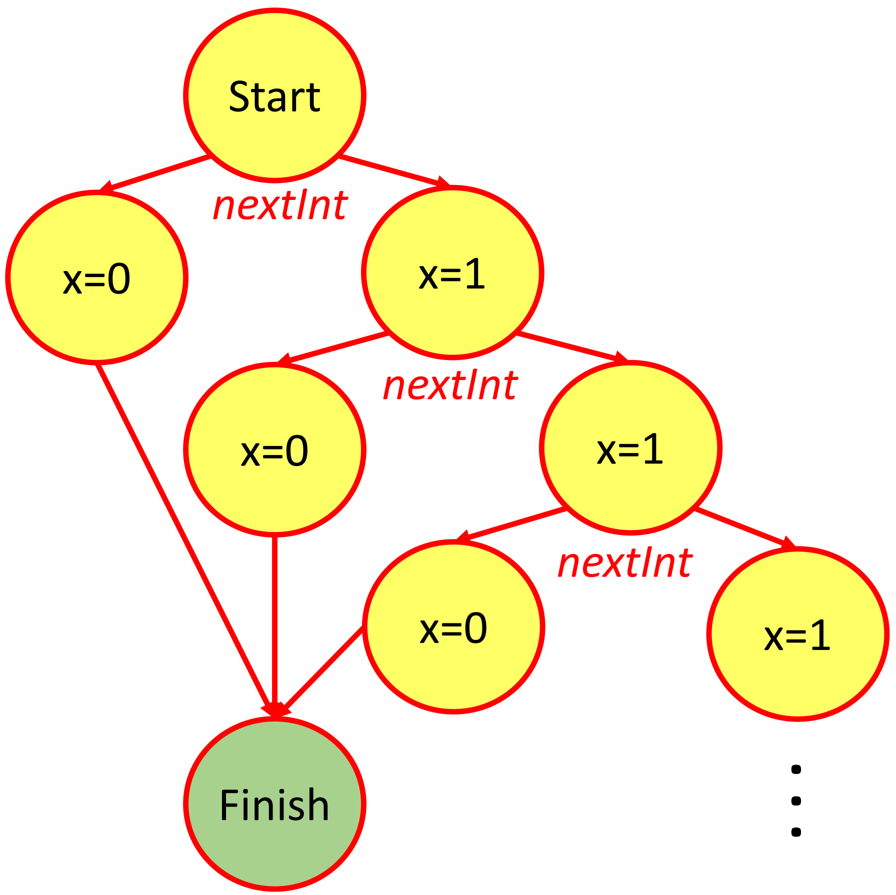


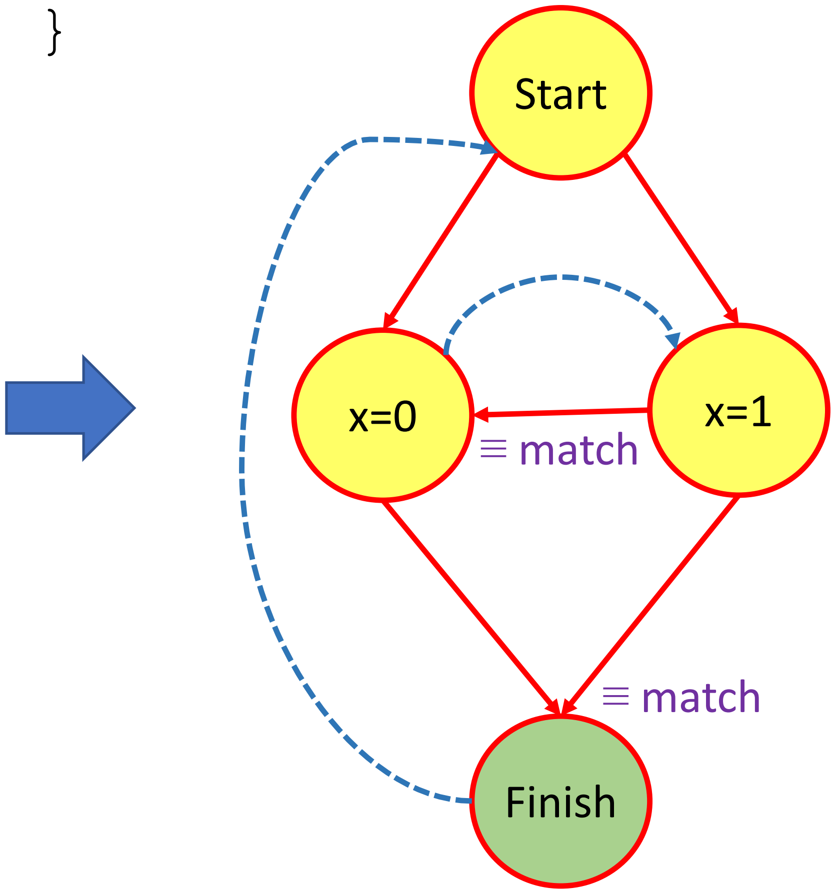


Number of states = **2*N+2**

Match & Backtrack on

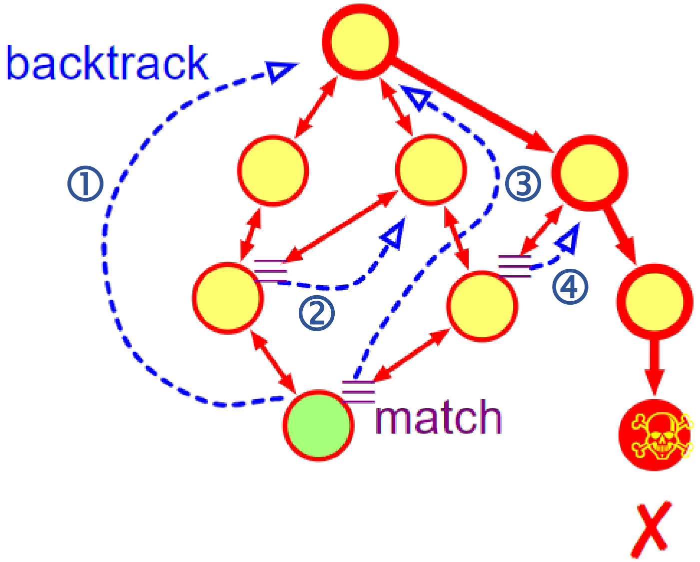
```
while(true) {
  x = rand.nextInt(2);
  if(x == 0) break;
}
```





Number of states = 4

Efficient State Exploration with Backtracking



Circles: Program states
Arrows: State transitions

- State divergence happens when there is a *choice* (e.g. random number generation)
- **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

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);
      }
}
```

Still, State Space can be Infinite (or Too Big)

- Even with backtracking, state space can be infinite (or too big)

- Cannot prove program correct if checker does not terminate in time
  - But can still find many defects in the process!

- Checker tries to test as many behaviors as possible (within given time)
  - By prioritizing states that test new behaviors, using heuristics
  - That way, more likely to find defects

What is Program State?

- 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
  - JVM maintains a stack (for local variables) and a heap (for objects)
  - That state is *much* smaller than your entire memory space
- Choice of programming language is important for model checking too
  - As well as for compiler static analysis
  - Memory managed languages like Java or C# tend to fair better

Java Path Finder (JPF)

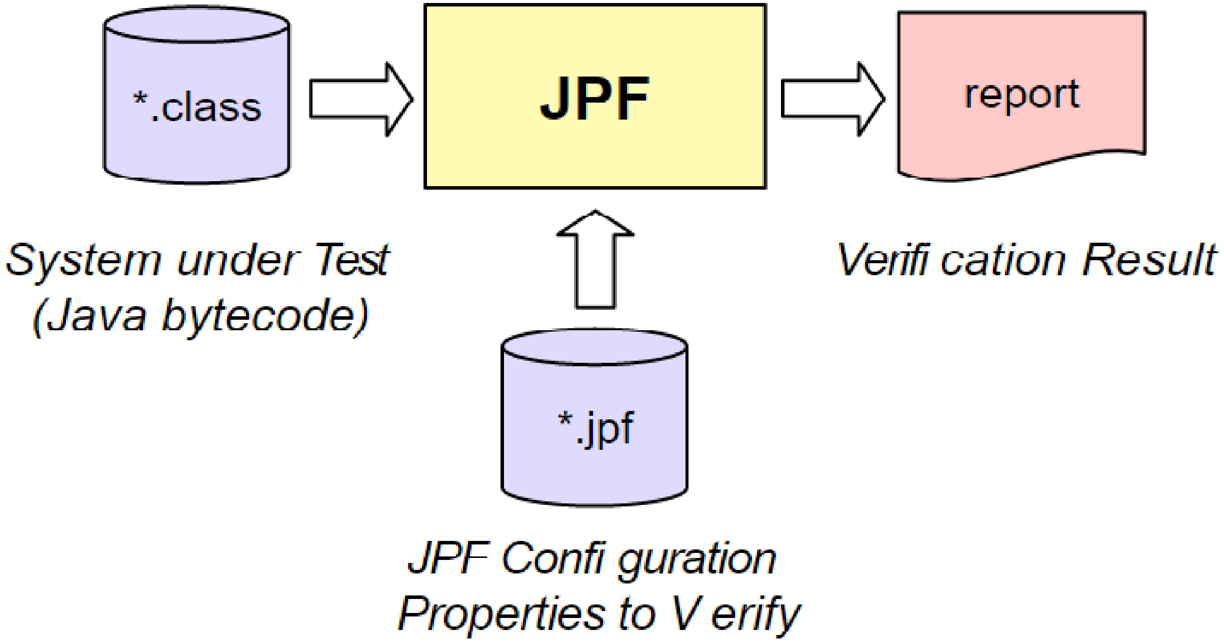
A Model Checker for Java

Java Path Finder (JPF)

- A model checker for Java: Uses all the principles we learned
  - Called Path Finder because it explores all possible paths in a program
  - Including paths that go through interleavings in a multithreaded program (!)
- Developed and maintained by NASA
  - For the purpose of rigorously model checking code for their space missions
- Open Source / Apache License Version 2
- Released 2010, still actively maintained and extended

Java Path Finder: How to Run

- Set main method class in the configuration (.jpf) file:
  `target = TestRunner`
- JPF checks target class according to configuration, generates report



Java Path Finder: Example Configuration File

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

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

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

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

```
=========================================== system under test
JPFTester.main()

=========================================== search started: 3/27/20 12:38 AM
3 - 4 = -1
3 - 6 = -3
4 - 4 = 0
4 - 6 = -2
5 - 4 = 1
5 - 6 = -1
=========================================== results
no errors detected
…
=========================================== search finished: 3/27/20 12:38 AM
```

Output of:

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

Java Path Finder with JUnit

Running JUnit on top of Java Path Finder

Leveraging JPF for JUnit Testing

- Instead of writing test cases for one or two input values
  → Enumerate a large set of input values and all their combinations
  → Use Verify API for this purpose

- For a nondeterministic program with random value generation
  → Enumerate all random values to prove test case always passes
  → Just set "cg.enumerate_random = true" in the .jpf configuration file

- For a nondeterministic program due to thread interleavings
  → Enumerate all possible thread interleavings (!)

(Possible) JUnit Class for JPF Testing

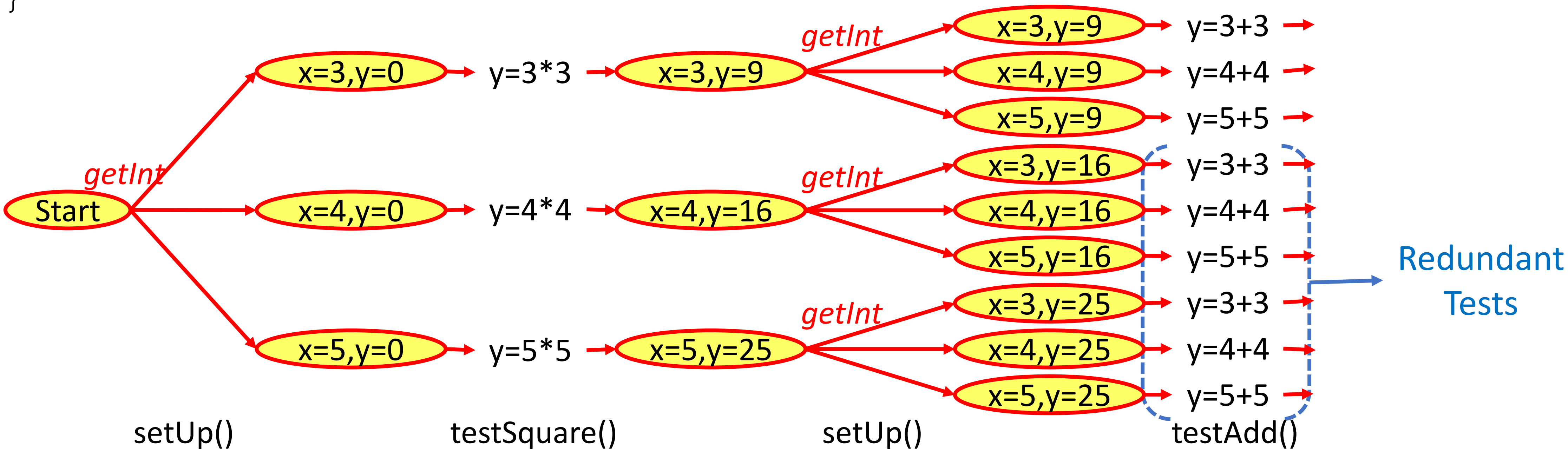
```
public class testArithmetic {
  private int x = 0;
  private int y = 0;

  @Before public void setUp() {
    x = Verify.getInt(3, 5);
  }
  @Test public void testSquare() {
    y = x * x;
    assert y > 0;
  }
  @Test public void testAdd() {
    y = x + x;
    assert y == 2 * x;
  }
}
```

→ Correct but leads to a lot of unnecessary testing!

@Before Re-enumerates x Before Every Test

```
@Before public void setUp() {
  x = Verify.getInt(3, 5);
}
```



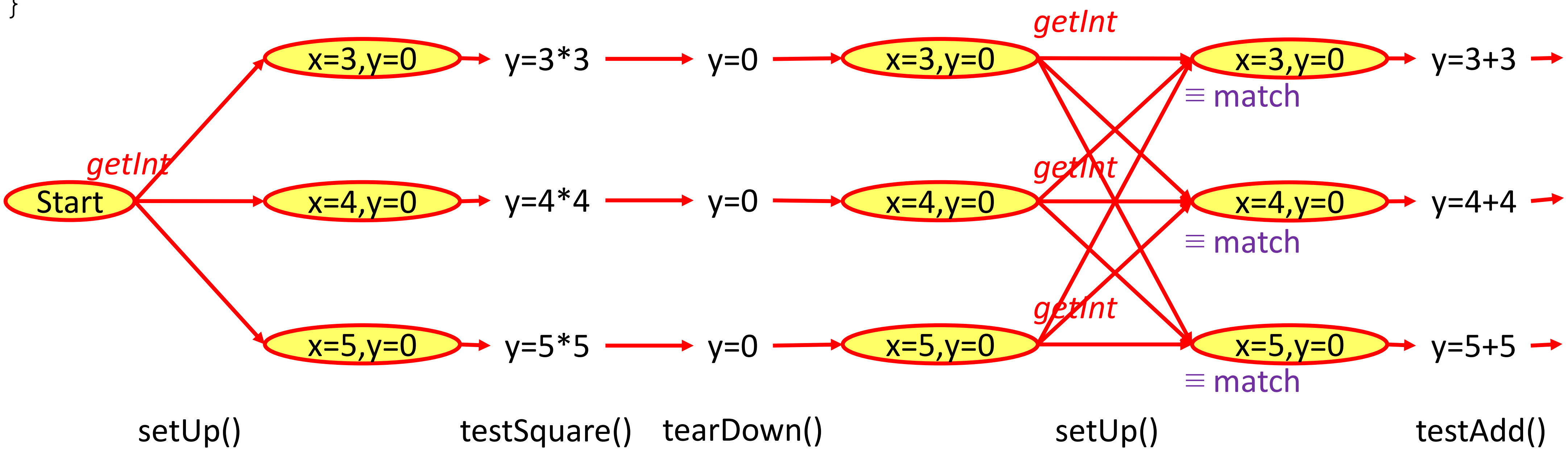
(Fixed) JUnit Class for JPF Testing

```
public class testArithmetic {
  private int x = 0;
  private int y = 0;

  @Before public void setUp() {
    x = Verify.getInt(3, 5);
  }
  @After public void tearDown() {
    y = 0;  // Return to initial state before next setup()
  }
  @Test public void testSquare() {
    y = x * x;
    assert y > 0;
  }
  @Test public void testAdd() {
    y = x + x;
    assert y == 2 * x;
  }
}
```

Proper Teardown Allows State Matching

```
@After public void tearDown() {
  y = 0;
}
```



- But why re-enumerate x each time and perform matching? → A lot of wasted work!

(Better) JUnit Class for JPF Testing

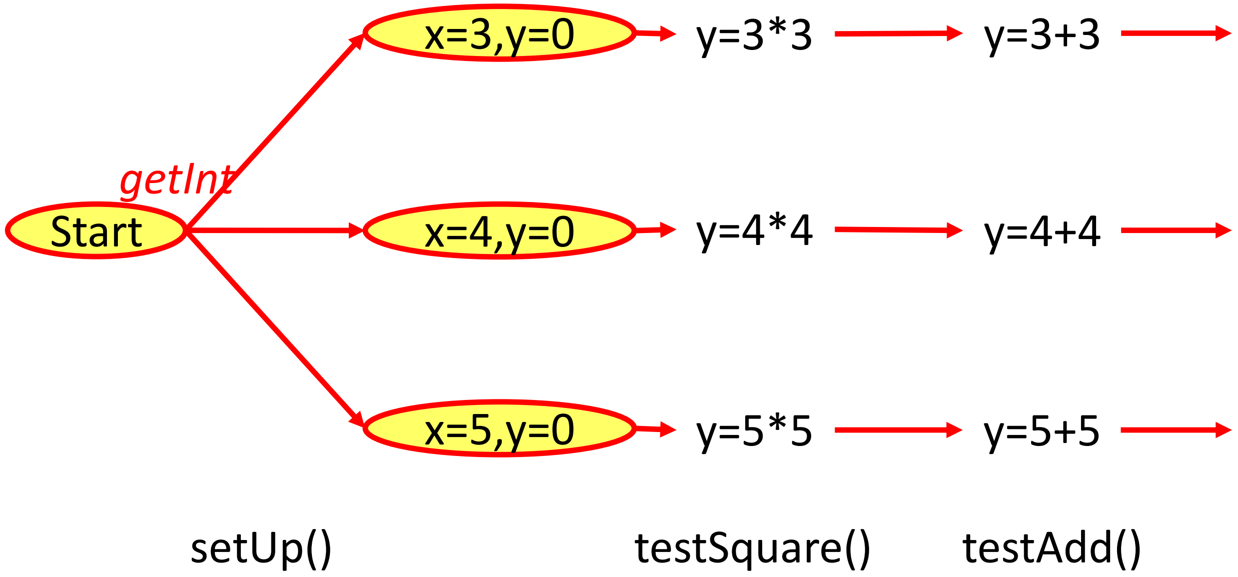
```
public class testArithmetic {
  private int x = 0;
  private int y = 0;

  @BeforeClass public static void setUp() {
    x = Verify.getInt(3, 5);
  }
  @Test public void testSquare() {
    y = x * x;
    assert y > 0;
  }
  @Test public void testAdd() {
    y = x + x;
    assert y == 2 * x;
  }
}
```

→ @BeforeClass is called only once before all the tests in the class

@BeforeClass Enumerates x Only Once

```
@BeforeClass public static void setUp() {
    x = Verify.getInt(3, 5);
}
```



- Much simpler and more efficient, don't you agree?

Interpreting JPF Report with JUnit Testing

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

== system under test

TestRunner.main() **JUnit test runner**

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

testCase1: expected:<0> but was:<1>

testCase2: expected:<“one”> but was:<“two”>

Output of JUnit:
Where you will find the error messages

== results

no errors detected **JUnit itself does not have any errors so it will always say this**

…

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

What if there are Too Many States?

- State explosion can cause JPF to run for hours, or even forever

- Some mitigation techniques
  - Limit the range of input values you test using Verify API
  - Limit the part of the code you model check
    - E.g. check only the part that is critical (in terms of security, safety, …)
    - E.g. check only the part that is hard to verify using conventional testing
  - Limit number of states created using @FilterField

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