JavaPathfinder Tutorial
02/2010

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Objectives and Roadmap

- Objectives
  - get basic understanding of what JPF is
  - learn by example what (current) JPF can be used for
  - learn what it takes to install, configure and run JPF
  - learn how JPF can be extended

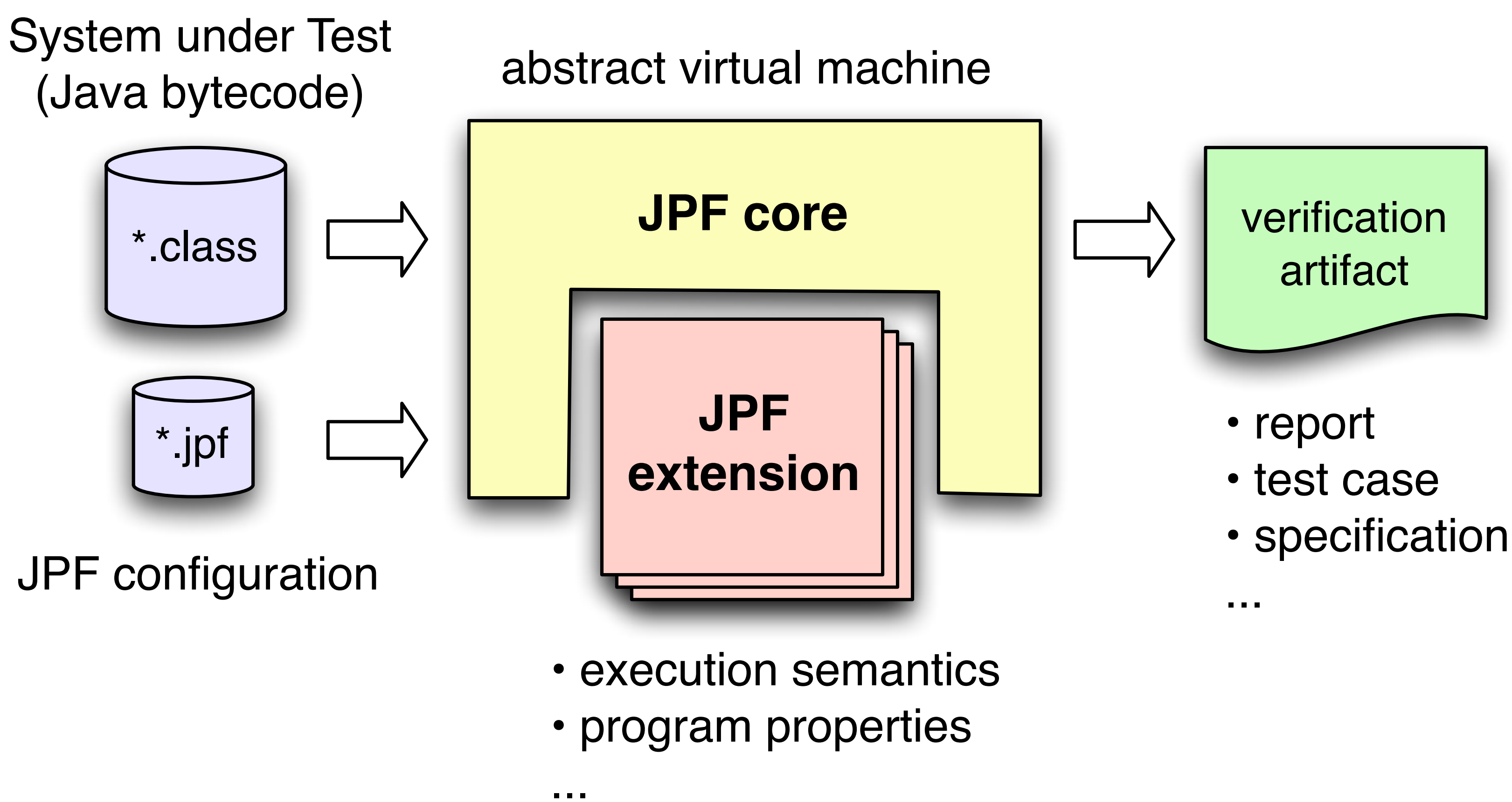
learn → use → extend

- Roadmap

(1) Introduction	1.0h
(2) Application Examples	2.0h
(3) Installation,Configuration and Invocation	1.0h
(4) Extension Mechanisms	1.5h
(5) Discussion	

Introduction - What Is JPF?

- surprisingly hard to summarize - can be used for many things
- extensible virtual machine framework for Java bytecode verification: workbench to efficiently implement all kinds of verification tools



- typical use cases:
  - software model checking (deadlock & race detection)
  - deep inspection (numeric analysis, invalid access)
  - test case generation (symbolic execution)

Example - What has JPF been used for ?

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Objective: reproduce - *and analyze* - spurious deadlock in large web application

required stubbing, trace file >70MB, would have taken months to analyze manually

3 pairs of *missed signals* in set of 18 threads
missed signal = thread A signals before thread B waits
→ B is blocked on "lost" signal

```
============================================= error #1
deadlock encountered:
  thread index=0,name=main,status=TERMINATED
  thread index=1,name=Thread-0,status=WAITING
  thread index=2,name=Thread-1,status=TERMINATED
  thread index=3,name=Thread-2,status=WAITING
  ...
                                         thread #
   6       8       2       3       7       1       4      trans    insn      loc
------- ------- ------- ------- ------- ------- ------- ----------------------
W:70279    |       |       |       |       |       |     123009 invokevirt awtMutex.java:38 : try {wait();}
  wait     |       T   terminate   |       |       |     123008     return MessageAnalyzer.java:341 : }
   |    W:72130    |       |       |       |       |     122597 invokevirt MessageAnalyzer.java:96 : wai
   |       S       |       |       |       |       |     122593
   |       |    A:70279    |  wait |       |       |     122572 invokevirt awtMutex.java:48 : notifyAll();
   |       |  signal   W:48205  terminate  |       |     122541 invokevirt awtQueue.java:182 : wait();
   |       |       |       |       T       |       |     122538     return EnforceSendMessageThread.java:39 :
   |       |       |       |   N:48205     |       |     122538 invokevirt awtQueue.java:150 : notify();
   |       |       |     signal    |    W:1288     |         96 invokevirt Mutex.java:31 : wait();
A:1288     |       |       |       |     wait      |         87 invokevirt Mutex.java:44 : notifyAll();
   |   signal      |       |       S       |       |         33
   S       |       |       |       |       |       |         33
   |       |       |       |       |       |   W:48252       29 invokevirt awtQueue.java:182 : wait();
   |       |       |       |       |       |       S          9
   |       |       |       S       |       |       |          7
   |       |       S       |       |       |       |          2
   |       |       |       |       |       S       |          0

...

============================================= statistics
elapsed time:        3:53:23
states:              new=123010, visited=235893, backtracked=357879, end=81378
search:              maxDepth=1023, constraints=0
choice generators:   thread=94664, data=0
heap:                gc=599818, new=7687542, free=12860670
instructions:        276556150
max memory:          9838MB
```

just one success story for the type of deep defects targeted by JPF

Who is using JPF ?

- major user group is academic research - collaborations with >20 universities worldwide (uiuc.edu, unl.edu, byu.edu, umn.edu, Stellenbosch Za, Waterloo Ca, AIST Jp, Charles University Prague Cz, ..)
- companies not so outspoken (exception Fujitsu - see press releases, e.g. http://www.fujitsu.com/global/news/pr/archives/month/2010/20100112-02.html) , but used by several Fortune 500 companies
- lots of (mostly) anonymous and private users (~1000 hits/day on website, ~10 downloads/day, ~60 read transactions/day, initially 6000 downloads/month)
- many uses inside NASA, but mostly model verification at Ames Research Center

History

- not a new project: around since 10 years and continuously developed:
  - 1999 - project started as front end for Spin model checker
  - 2000 - reimplementation as concrete virtual machine for software model checking (concurrency defects)
  - 2003 - introduction of extension interfaces
  - 2005 - open sourced on Sourceforge
  - 2008 - participation in Google Summer of Code
  - 2009 - moved to own server, hosting extension projects and Wiki

Awards

- widely recognized, awards for JPF in general and for related work, team and individuals
  - 2002 - ACM Sigsoft Distinguished Paper award
  - 2003 - “Turning Goals into Reality” (TGIR) Engineering Innovation Award from the Office of AeroSpace Technology
  - 2004, 2005 - Ames Contractor Council Awards
  - 2007 - IBM's Haifa Verification Conference (HVC) award
  - 2009 - “Outstanding Technology Development” award of the Federal Laboratory Consortium for Technology Transfer (FLC)

Caveat emptor - Costs of JPF application

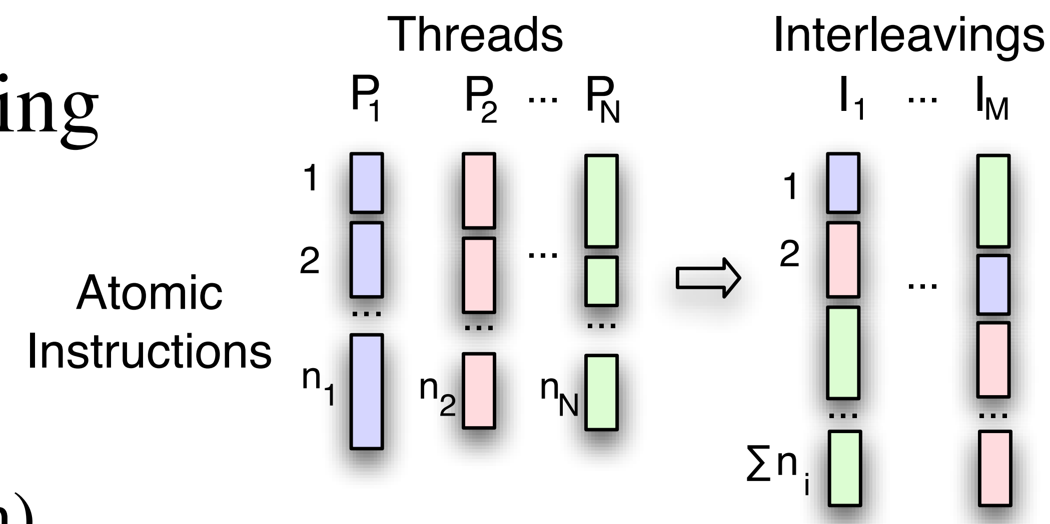
- you need to learn
  - JPF is not a lightweight tool
  - flexibility has its price - configuration can be intimidating
  - might require extension for your SUT (properties, libraries)

- you will encounter unimplemented/missing parts (e.g. UnsatisfiedLinkError)
  - usually easy to implement
  - exception: state-relevant native libraries (java.io, java.net)
  - can be either modeled or stubbed

- you need suitable test drivers for concrete inspection & SMC

JPF's Challenges

- **theoretical**: model checking scalability
  $\Rightarrow$ optimization,
  adaptation (config),
  research (collaboration)



$$M = \frac{(\Sigma_{i=1}^{N} n_i)!}{\Pi_{i=1}^{N}(n_i!)}$$

- **technical**:
  - Java VM + libraries HUGE
    a lot of ground to cover
    $\Rightarrow$ reuse (libs, where possible)
  - JPF is research platform *and* production tool at the same time
    $\Rightarrow$ open sourcing (but no free lunch)

Java	files	loc	MB
OpenJDK	12,000	3.10E+06	118
JPF	1,600	2.04E+05	6

- **organizational**:
  - small inhouse developer team
    $\Rightarrow$ relies on external collaboration

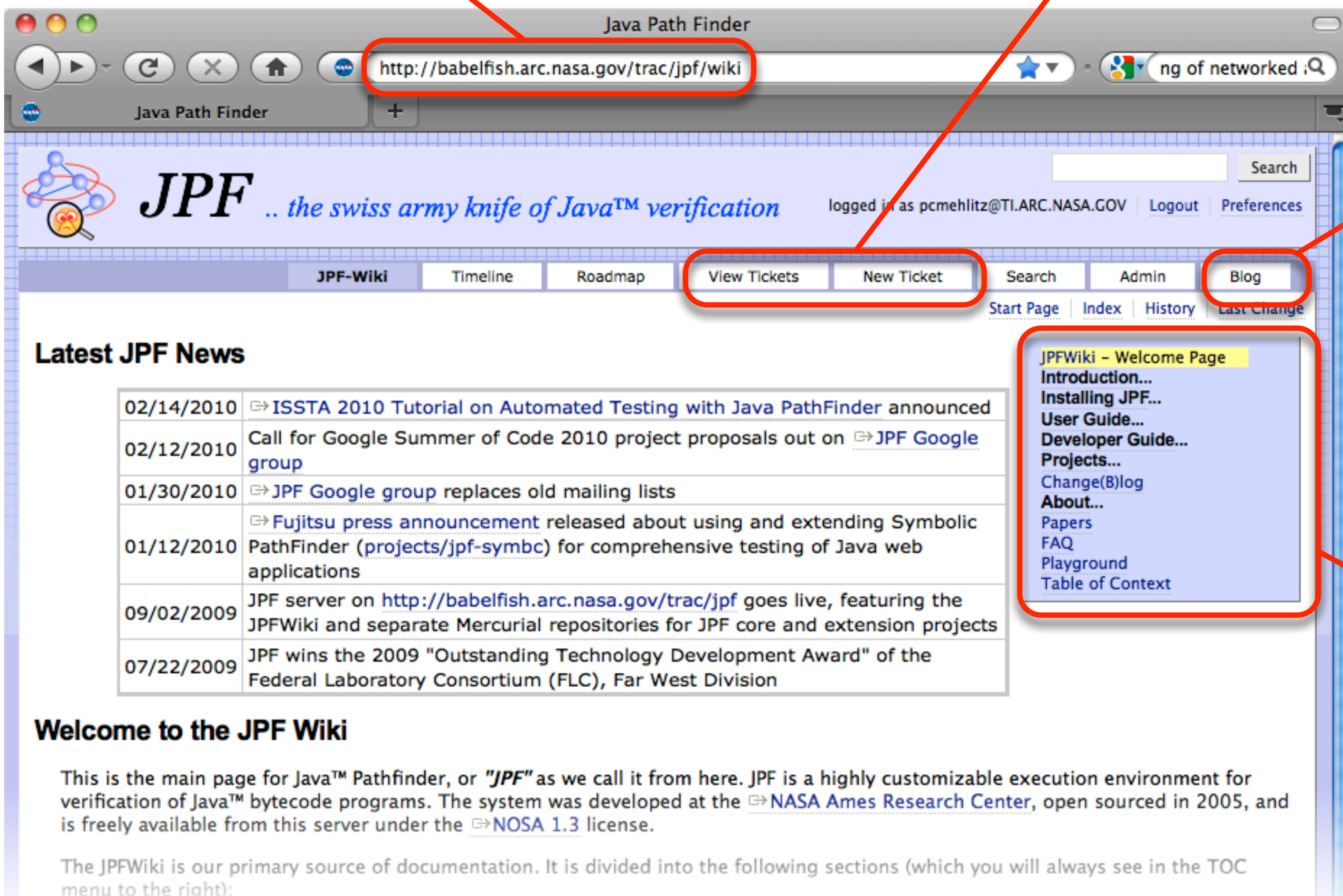
Where to learn more - the JPF-Wiki

http://babelfish.arc.nasa.gov/trac/jpf

- public read access
- edit for account holders (also non-NASA)

bug tracking

- Trac ticket system



project blog

- announcements
- important changes

hierarchical navigation menu

- intro
- installation
- user docu
- developer docu
- **extension projects**

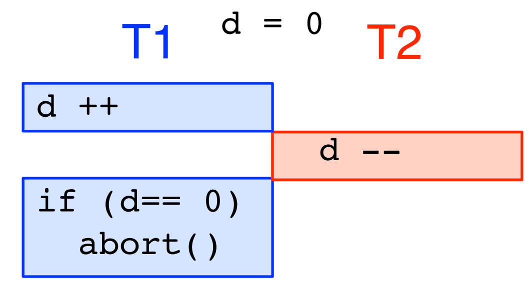
Introduction: Key Points

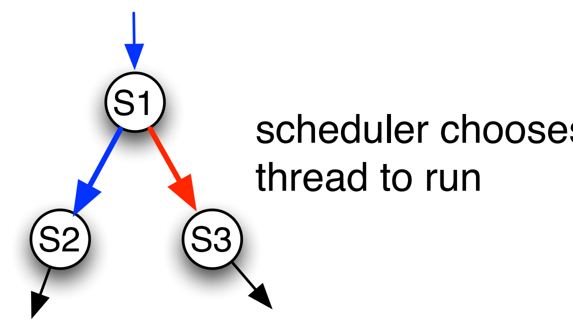
- JPF is research platform *and* production tool (basis)
- JPF is designed for extensibility
- JPF is open source
- JPF is an ongoing collaborative development project
- JPF cannot find all bugs
  - but as of today -
    some of the most expensive bugs only JPF can find
- JPF is moderately sized system (~200ksloc core + extensions)
- JPF represents >20 man year development effort
- JPF is pure Java application (platform independent)

Examples

goal is to show gamut of possible applications, not detailed defect understanding

- software model checking (SMC) of production code
  - data acquisition (random, user input)
  - concurrency (deadlock, races)





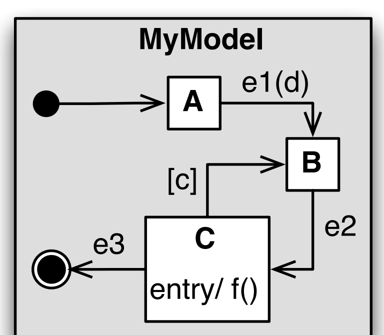
- deep inspection of production code
  - property annotations (Const, PbC,..)
  - numeric verification (overflow, cancellation)

```
@Const
int dontChangeMe() {..}
```

```
double x = (y - z) * c
```

numeric error of x?

- model verification
  - UML statecharts



does model work?

- test case generation

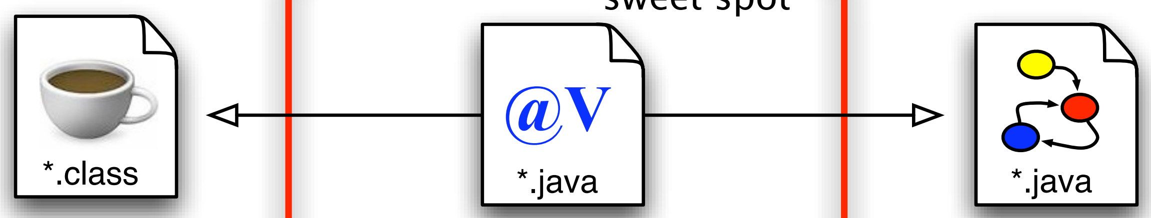
- verification of distributed application

Application Types

JPF unaware programs | *JPF enabled programs* | *JPF dependent programs*

runs on any JVM

"sweet spot"



runs only under JPF

constraints

runtime costs
- order of magnitude slower
- state storage memory

standard library support
- java.net, javax.swing, ..
  (needs abstraction models)

functional property impl. costs
- listeners, MJI knowledge

restricted choice types
- scheduling sequences
- java.util.Random

annotate program
- requirements
- sequences (UML)
- contracts (PbC)
- tests

...

analyze program
- symbolic exec
  → test data
- thread safety / races

restricted application models
- UML statemachines
- does not run w/o JPF libraries

initial domain impl. costs
- domain libs can be tricky

benefits

non-functional properties
- unhandled exceptions
  (incl. AssertionError)
- deadlocks
- races

improved inspection
- coverage statistics
- exact object counts
- execution costs

low modeling costs
- statemachine w/o layout hassle,..

functional (domain) properties
- built-in into JPF libraries

flexible state space
- domain specific choices
  (e.g. UML "enabling events")

runtime costs & library support
- usually not a problem, domain
  libs can control state space

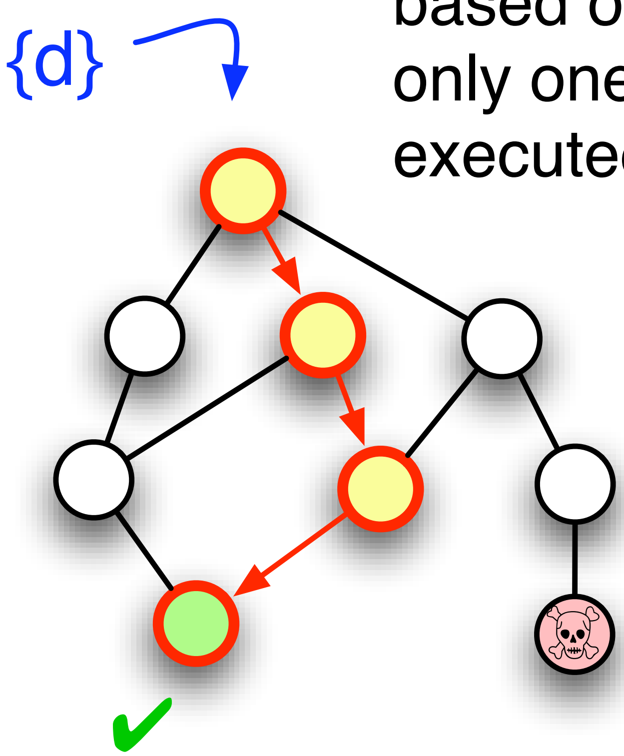
Examples: Software Model Checking

- focus is on *production code*, i.e. SUT applications are not specifically written for JPF
- might include abstracted/modeled libraries, but no modified SUT behavior
- objective: check execution paths that are hard or impossible to test reliably (scheduling sequences, large input spaces, mix between both)
- classic application: detect concurrency defects

Model Checking vs. Testing

- SMC is a rigorous formal method
- SMC does not suffer from false positives (like static analysis)
- SMC provides traces (execution history) when it finds a defect

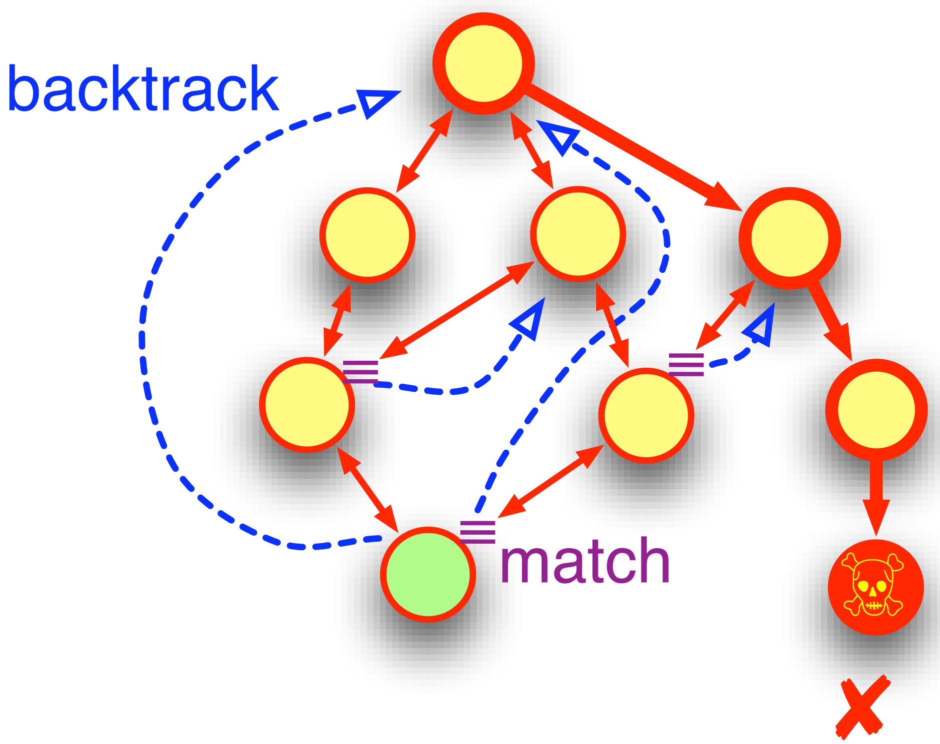
testing:



based on input set {d}
only one path
executed at a time

model checking:

all program state are explored
until none left or defect found



Wednesday, February

Model Checking vs. Debugging

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- JPF automatically *finds* defects to debug
- program traces - JPF *remembers* whole execution history that lead to defect
- automatic trace analysis capability *explains* defects

```
deadlock encountered:
 thread index=1,name=Thread-0,status=WAITING,...
 thread index=2,name=Thread-1,status=WAITING,...
...
------------------------ transition #32 thread: 2
 oldclassic.java:127  : event1.signal_event();
 oldclassic.java:71   : count = (count + 1) % 3;
 oldclassic.java:74   : notifyAll();
 oldclassic.java:75   : }
 oldclassic.java:129  : if (count == event2.count)
------------------------ transition #33 thread: 1
 oldclassic.java:103  : event1.wait_for_event();
 oldclassic.java:79   : wait();
...
```

Trace Analysis

```
   2        1      trans   loc
-------- -------- -----------------------
W:303       |       35   oldclassic.java:79 : wait();
   |     W:302      34   oldclassic.java:79 : wait();
A:302       |       32   oldclassic.java:74 : notifyAll();
   |     A:303      28   oldclassic.java:74 : notifyAll();
```

Example 1: Nondeterministic Data (1)

- Source

```
..   public static void main (String[] args) {
..     ...
 7:    Random random = new Random(42);      // (1)
 8:    int a = random.nextInt(2);           // (2)
..     ...
13:    int b = random.nextInt(3);           // (3)
..     ...
16:    int c = a/(b+a -2);                  // (4)
..     ...
..   }
```

- Config

```
cg.enumerate_random = true
```

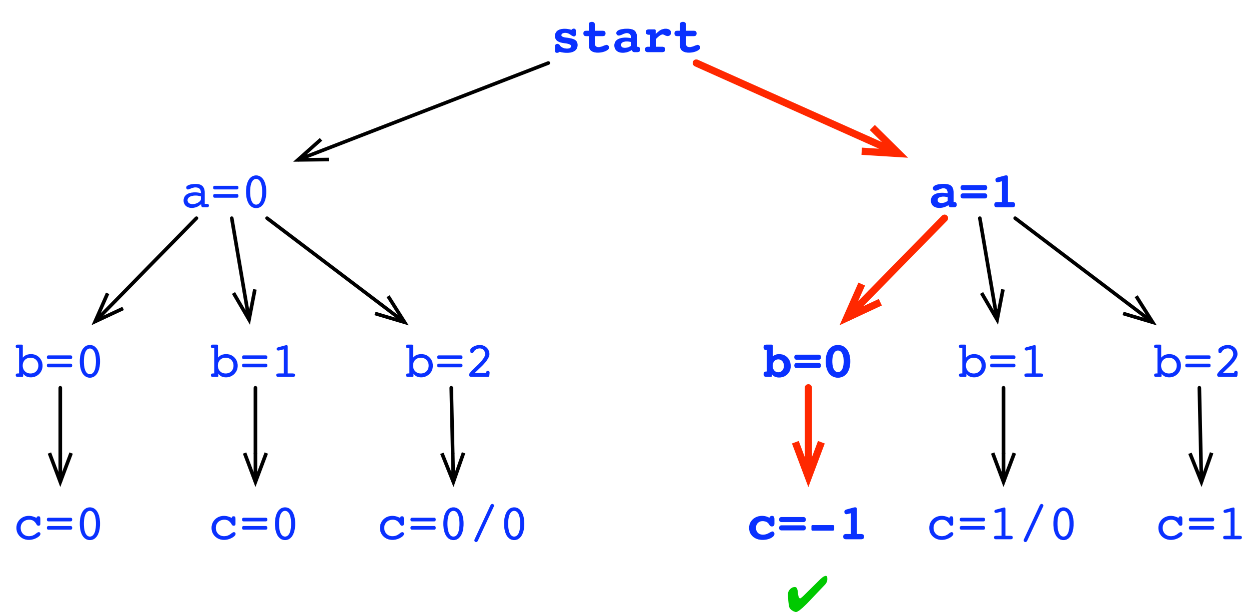
- Output

```
...
================================== search started: 2/10/10 6:08 PM
computing c = a/(b+a - 2)..
a=0
  b=0        ,a=0
=>  c=0      ,a=0,b=0
  b=1        ,a=0
=>  c=0      ,a=0,b=1
  b=2        ,a=0

================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.ArithmeticException: division by zero
        at Rand.main(Rand.java:16)
```

jpf-core/src/examples/Rand.jpf

Example 1: Nondeterministic Data (2)

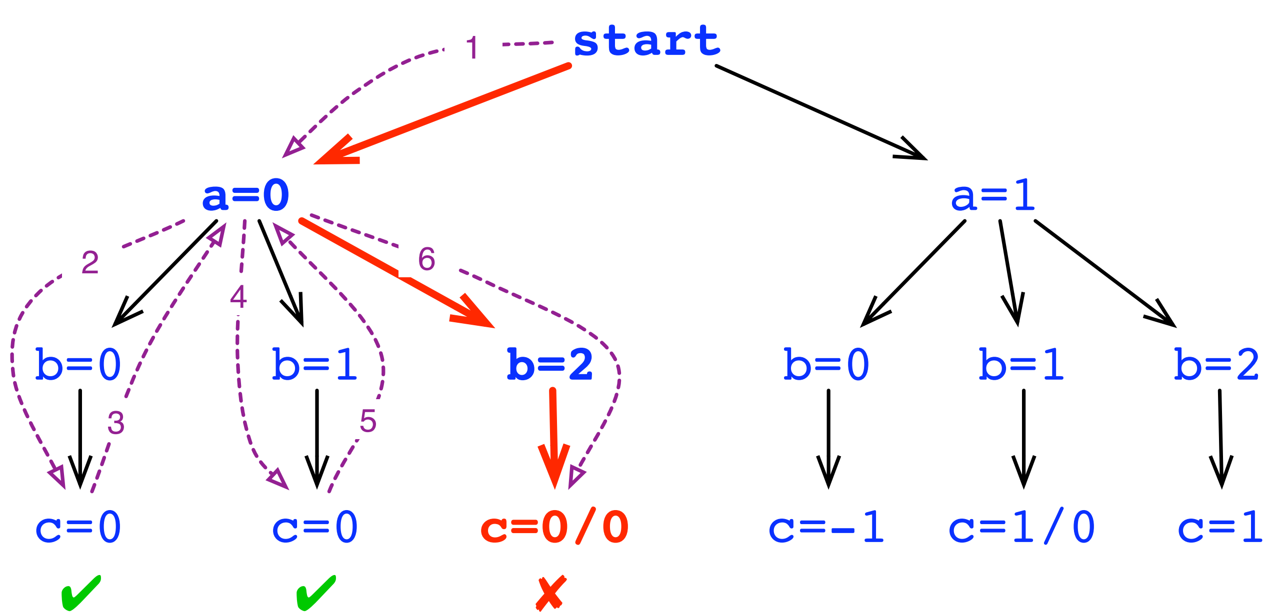
- Testing only covers one execution




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

```
>java Rand
  a=1
    b=0
      c=-1
```

- Model checking (theoretically) covers all executions




```
>jpf +cg.enumerate_random=true
        Rand
  a=0
    b=0
      c=0
    b=1
      c=0
    b=2
ERROR: ArithmeticException
```

Example 2: Data Race (1)

- Source

```
int d = 42;

public void run () {
     doSomething(1001);                    // (1)
     d = 0;                                // (2)
}

public static void main (String[] args){
     Racer racer = new Racer();
     Thread t = new Thread(racer);
     t.start();

     doSomething(1000);                    // (3)
     int c = 420 / racer.d;                // (4)
     System.out.println(c);
}
```

jpf-core/src/examples/Racer.jpf

Example 2: Data Race (1)

- Source

```
int d = 42;

public void run () {
      doSomething(1001);                          // (1)
      d = 0;                                      // (2)
}

public static void main (String[] args){
      Racer racer = new Racer();
      Thread t = new Thread(racer);
      t.start();

      doSomething(1000);                          // (3)
      int c = 420 / racer.d;                      // (4)
      System.out.println(c);
}
```

data race

jpf-core/src/examples/Racer.jpf

Example 2: Data Race (2)

- Config

```
listener = gov.nasa.jpf.listener.PreciseRaceDetector
report.console.property_violation = error,trace
```

- Output

```
...
================================ search started: 2/10/10 6:32 PM
10
10
================================ error #1
gov.nasa.jpf.listener.PreciseRaceDetector
race for field Racer@287.d
  main at Racer.main(Racer.java:16)
              "int c = 420 / racer.d;              "  : getfield
  Thread-0 at Racer.run(Racer.java:7)
              "d = 0;                              "  : putfield
================================ trace #1
----------------------------------------- transition #0 thread: 0
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>main}
      [2843 insn w/o sources]
  ...
  Racer.java:16                  : int c = 420 / racer.d;
----------------------------------------- transition #4 thread: 1
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {main,>Thread-0}
  ...
  Racer.java:7                   : d = 0;
----------------------------------------- transition #5 thread: 0
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>main,Thread-0}
  Racer.java:16                  : int c = 420 / racer.d;
```

Example 3: Deadlock (1)

```
class FirstTask extends Thread {
  Event event1, event2;
  int   count = 0;
  ...
  public void run () {
    count = event1.count;

    while (true) {
      if (count == event1.count) {
        event1.wait_for_event();
      }

      count = event1.count;
      event2.signal_event();
    }
  }
}
```

```
class SecondTask extends Thread {
  Event event1, event2;
  int   count = 0;
  ...
  public void run () {
    count = event2.count;

    while (true) {
      event1.signal_event();

      if (count == event2.count) {
        event2.wait_for_event();
      }

      count = event2.count;
    }
  }
}
```

```
class Event {
  int count = 0;

  public synchronized void signal_event () {
    count++;  notifyAll();
  }
  public synchronized void wait_for_event () {
    .. wait(); ..
  }
}
```

jpf-core/src/examples/oldclassic.jpf

Example 3: Deadlock (2)

- Report - shows what happened, but not easily why

```
JavaPathfinder v5.x - (C) RIACS/NASA Ames Research Center

======================== system under test
application: oldclassic.java

======================== search started: 2/11/10 11:10 AM
1
  2
1
  2
1
...

========================= error #1
gov.nasa.jpf.jvm.NotDeadlockedProperty
deadlock encountered:
  thread index=0,name=main,status=TERMINATED,this=null,target=null,...
  thread index=1,name=Thread-0,status=WAITING,this=FirstTask@295,lockCount=1,...
  thread index=2,name=Thread-1,status=WAITING,this=SecondTask@322,lockCount=1,...
...
```

Example 3: Deadlock (3)

```
...
================== trace #1
------------------------------------- transition #0 thread: 0
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>main}
      [2843 insn w/o sources]
  oldclassic.java:47                : Event      new_event1 = new Event();
…
------------------------------------- transition #29 thread: 1
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-0,Thread-1}
  oldclassic.java:102               : if (count == event1.count) {
  oldclassic.java:103               : event1.wait_for_event();
------------------------------------- transition #30 thread: 2
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {Thread-0,>Thread-1}
  oldclassic.java:129               : if (count == event2.count) {
  oldclassic.java:133               : count = event2.count;
...
  oldclassic.java:126               : System.out.println("  2");
  oldclassic.java:127               : event1.signal_event();
...
  oldclassic.java:71                : count = (count + 1) % 3;
  oldclassic.java:74                : notifyAll();
  oldclassic.java:75                : }
  oldclassic.java:129               : if (count == event2.count) {
------------------------------------- transition #33 thread: 1
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-0,Thread-1}
  oldclassic.java:103               : event1.wait_for_event();
  oldclassic.java:79                : wait();
------------------------------------- transition #34 thread: 2
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-1}
  oldclassic.java:129               : if (count == event2.count) {
  oldclassic.java:130               : event2.wait_for_event();
  oldclassic.java:79                : wait();
```

Example 3: Deadlock (3)

```
...
================== trace #1
------------------------------------- transition #0 thread: 0
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>main}
      [2843 insn w/o sources]
  oldclassic.java:47              : Event      new_event1 = new Event();
…
------------------------------------- transition #29 thread: 1
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-0,Thread-1}
  oldclassic.java:102             : if (count == event1.count) {
  oldclassic.java:103             : event1.wait_for_event();
------------------------------------- transition #30 thread: 2
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {Thread-0,>Thread-1}
  oldclassic.java:129             : if (count == event2.count) {
  oldclassic.java:133             : count = event2.count;
...
  oldclassic.java:126             : System.out.println("  2");
  oldclassic.java:127             : event1.signal_event();
...
  oldclassic.java:71              : count = (count + 1) % 3;
  oldclassic.java:74              : notifyAll();
  oldclassic.java:75              : }
  oldclassic.java:129             : if (count == event2.count) {
------------------------------------- transition #33 thread: 1
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-0,Thread-1}
  oldclassic.java:103             : event1.wait_for_event();
  oldclassic.java:79              : wait();
------------------------------------- transition #34 thread: 2
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-1}
  oldclassic.java:129             : if (count == event2.count) {
  oldclassic.java:130             : event2.wait_for_event();
  oldclassic.java:79              : wait();
```

missed signal

Example 3: Deadlock (4)

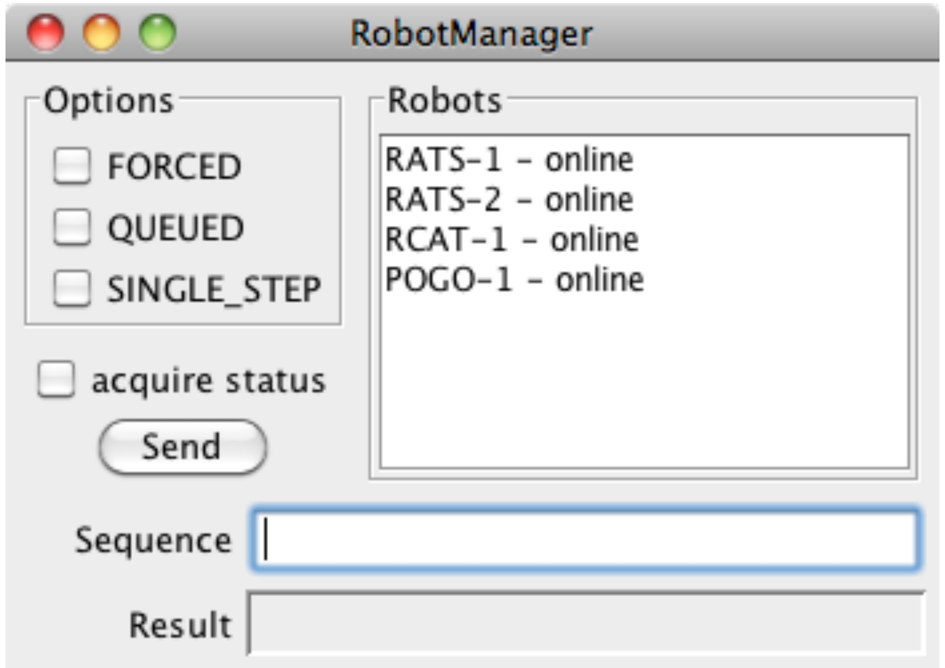
```
report.console.property_violation = error,snapshot
listener = .listener.DeadlockAnalyzer
```

```
===================== error #1
gov.nasa.jpf.jvm.NotDeadlockedProperty
deadlock encountered:
...
===================== snapshot #1
thread index=1,name=Thread-0,status=WAITING,this=FirstTask@295 ...
  waiting on: Event@290
  call stack:
        at Event.wait_for_event(oldclassic.java:79)
        at FirstTask.run(oldclassic.java:103)

thread index=2,name=Thread-1,status=WAITING,this=SecondTask@322 ...
  waiting on: Event@291
  call stack:
        at Event.wait_for_event(oldclassic.java:79)
        at SecondTask.run(oldclassic.java:130)

====================== thread ops #1
   2       1      trans    insn     loc
------- ------- ----------------------
W:291      |        37 invokevirt oldclassic.java:79 : wait();
   |    W:290       36 invokevirt oldclassic.java:79 : wait();
A:290      |        35 invokevirt oldclassic.java:74 : notifyAll();
   |    A:291       28 invokevirt oldclassic.java:74 : notifyAll();
   S       |         1
   |       S         0
```

Example 4: User Input Model Checking (1)

- specify user input in event script with alternatives

```
// enter command sequence
$Sequence:input.setText("turn")

// try all Options combinations
ANY { $<FORCED|QUEUED|SINGLE_STEP>.doClick() }
ANY { $<FORCED|QUEUED|SINGLE_STEP>.doClick() }
ANY { $<FORCED|QUEUED|SINGLE_STEP>.doClick() }

// select robot
ANY { $Robots:list.setSelectedIndex(0|1|2|3) }

// send sequence
$Send.doClick()
```




```
input.setText(..)
FORCED.doClick()
FORCED.doClick()
FORCED.doClick()
list.setSelectedIndex(0)
Send.doClick()
```

```
input.setText(..)
QUEUED.doClick()
...
```

...

```
input.setText(..)
SINGLE_STEP.doClick()
SINGLE_STEP.doClick()
SINGLE_STEP.doClick()
list.setSelectedIndex(3)
Send.doClick()
```

generated event sequences

Example 4: User Input Model Checking (2)

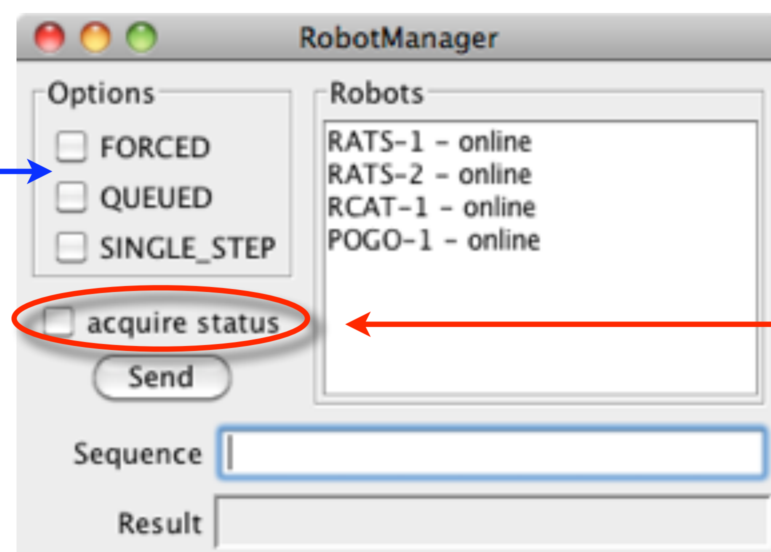
- Finds input combination that causes exception in user code:

```
============================================================ error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.AssertionError: POGOs cannot force queued sequences
         at POGO.processSequence(RobotManager.java:92)
         at RobotManager.sendSequence(RobotManager.java:264)
         ...

============================================================ choice trace #1
   0: gov.nasa.jpf.awt.UIActionSingleChoice[.. >$Sequence:input.setText("turn")]
   1: gov.nasa.jpf.awt.UIActionFromSet[.. >$FORCED.doClick(),
                                           $QUEUED.doClick(),
                                           $SINGLE_STEP.doClick()]
   2: gov.nasa.jpf.awt.UIActionFromSet[..  $FORCED.doClick(),
                                          >$QUEUED.doClick(),
                                           $SINGLE_STEP.doClick()]
   3: gov.nasa.jpf.awt.UIActionFromSet[..  $FORCED.doClick(),
                                           $QUEUED.doClick(),
                                          >$SINGLE_STEP.doClick()]
   4: gov.nasa.jpf.awt.UIActionFromSet[..  $Robots:list.setSelectedIndex(0),
                                           $Robots:list.setSelectedIndex(1),
                                           $Robots:list.setSelectedIndex(2),
                                          >$Robots:list.setSelectedIndex(3)]
   5: gov.nasa.jpf.awt.UIActionSingleChoice[.. >$Send.doClick()]
```

Example 5: Multithreaded GUI (1)

- extended GUI application that uses concurrent data acquisition
- thread structure not obvious because of large portions of framework / library code (swing)
- application logic mostly implemented as callback actions
- two overlaid non-determinisms: user input and scheduling sequence
- “impossible” to test

Thread 1:
user input



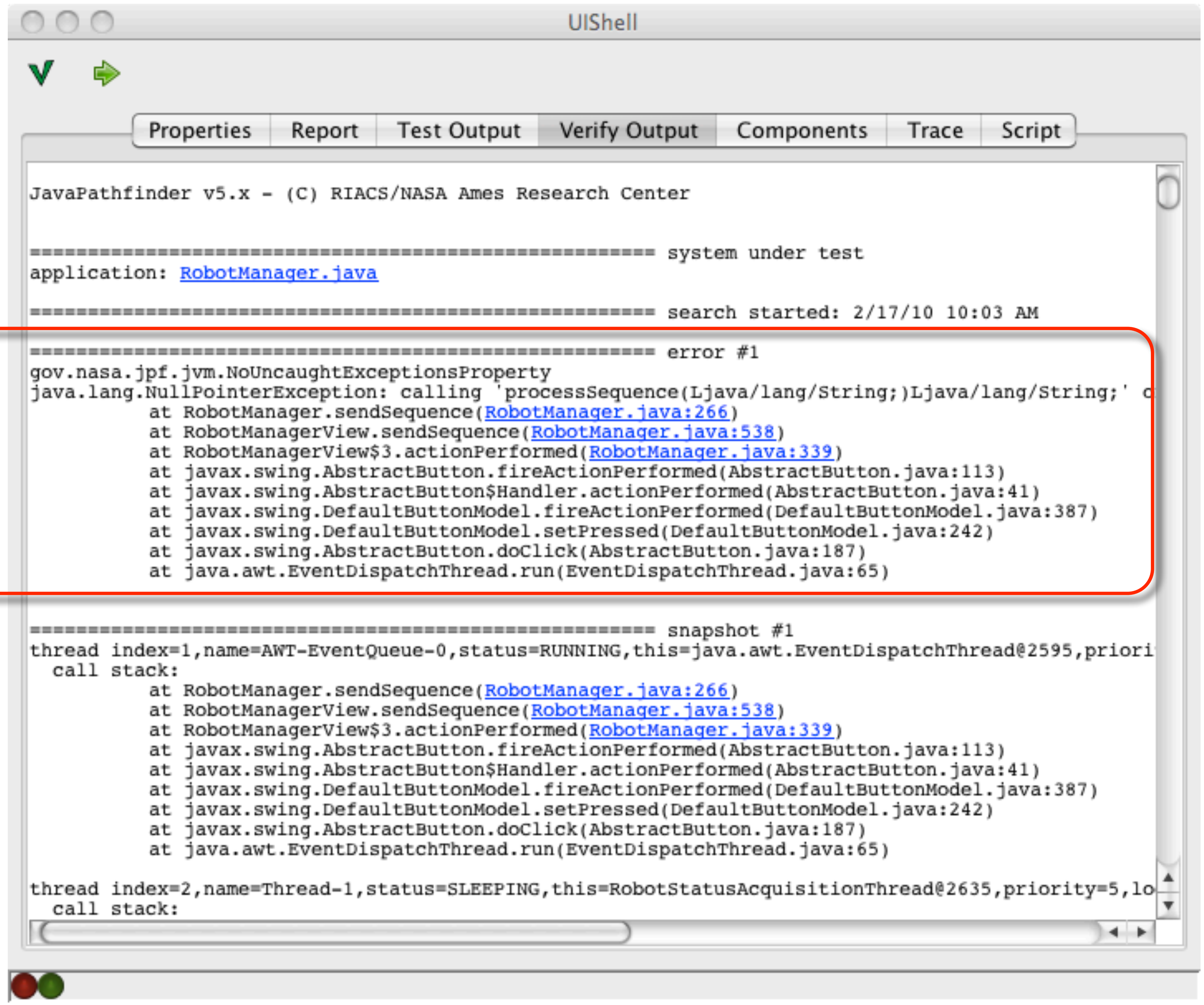
Thread 2:
data acquisition

jpf-awt/src/examples/RobotManager-thread.jpf

Example 5: Multithreaded GUI (2)

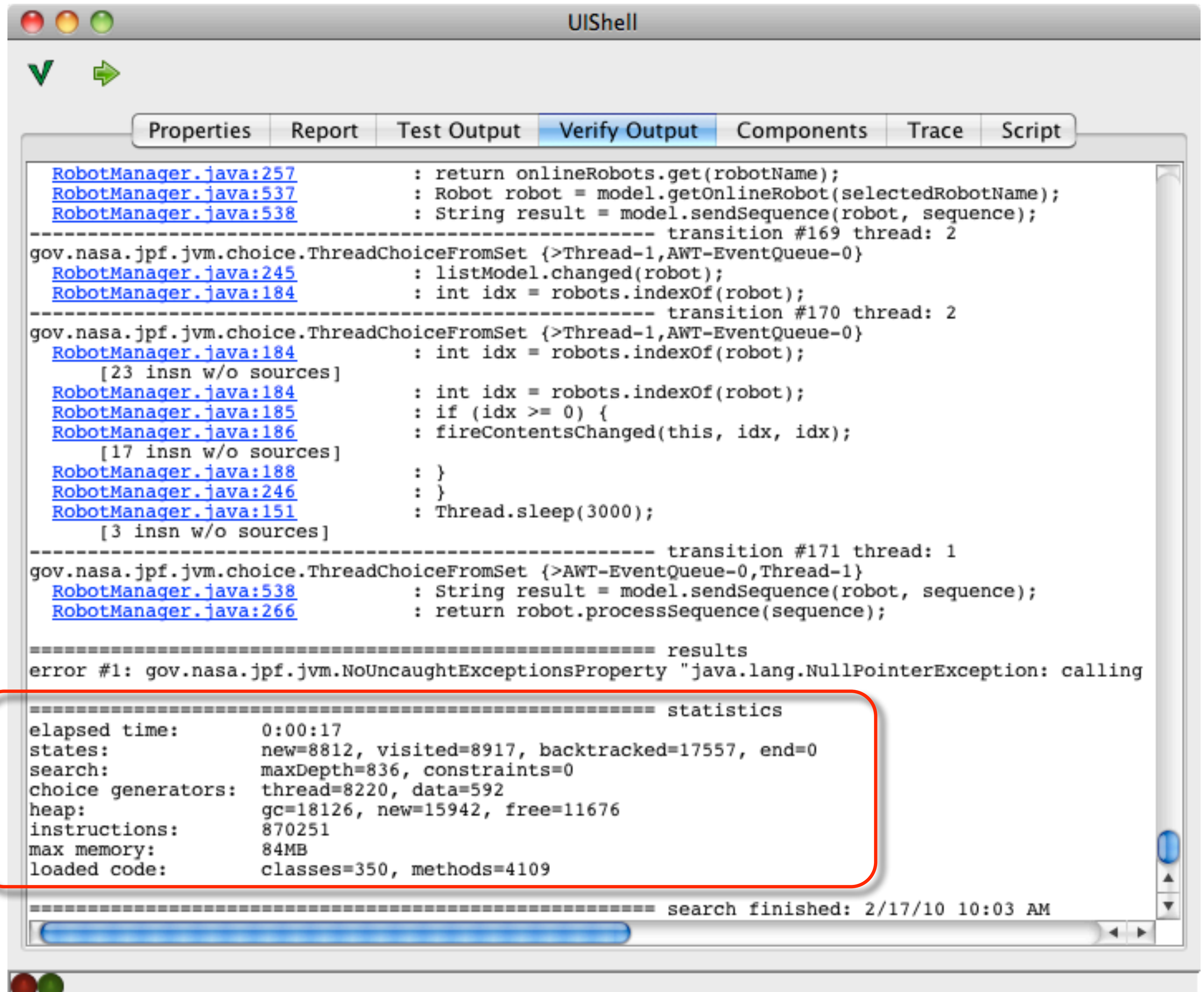
- JPF finds defect that is untestable, but..

general, low level defect



Example 5: Multithreaded GUI (3)

- trace too long to find out what causes it - needs more analysis



too deep
to understand

Example 5: Multithreaded GUI (4)

- generic trace analysis can help (e.g. hierarchical method execute/return log with MethodAnalyzer listener)
- still too time consuming in many cases

```
listener=.listener.MethodAnalyzer
method.include=*Robot*
...
```

thread 1

thread 2

```
…
1: .........R RobotManager.isRobotOnline(..)Z, RobotManager@287
------------------------------------------
…
2: ..X RobotManager.isRobotOnline(..)Z, RobotManager@287
------------------------------------------
1: .........X RobotManager.getOnlineRobot(..)LRobot;, RobotManager@287
------------------------------------------
…
2: ..R RobotManager.isRobotOnline(..)Z, RobotManager@287
2: ..X RobotManager.setRobotOnline(LRobot;Z)V, RobotManager@287
…
------------------------------------------
1: .........R RobotManager.getOnlineRobot(..)LRobot;, RobotManager@287
------------------------------------------
…
2: ..R RobotManager.setRobotOnline(LRobot;Z)V, RobotManager@287
------------------------------------------
1: .........X RobotManager.sendSequence(LRobot;..), RobotManager@287
```

Example 5: Multithreaded GUI (5)

- better approach - precise properties from annotations (user docu)
- self explaining error message (no need for further analysis)
- much more efficient to check

```
// means: RobotManager instances are not thread-safe, don't use them concurrently
@NonShared
public class RobotManager {
  ...
```

```
...
====================================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.AssertionError: NonShared object: RobotManager@287
     accessed in live thread cycle: AWT-EventQueue-0,Thread-1,AWT-EventQueue-0,main
         at RobotManager$ListModel.getSize(RobotManager.java:170)
         ...
====================================================== statistics
elapsed time:          0:00:01
states:                new=76, visited=0, backtracked=0, end=0
search:                maxDepth=75, constraints=0
choice generators:     thread=67, data=9
heap:                  gc=94, new=2668, free=212
instructions:          72884
...
```

self-explaining, doesn't even need trace

Examples: Deep Inspection

- focus is primarily on properties that require or benefit from VM level evaluation (execution history and details)
- checks do not modify SUT behavior (performed at VM level)
- orthogonal to path exploration (makes model checking more useful)
- can be based on “hints” (annotations) in SUT (JPF-aware application)
- can be just based on binary code (JPF unaware application)

Example 6: Const Annotation

- transitive properties (holds for certain dynamic scope)
- checked by dedicated listeners (runtime monitoring)
- does not require extensive annotation (const/var/unknown) of static analysis tools to avoid false positives

```
import gov.nasa.jpf.annotation.Const;

public class ConstViolation {
  int d;

  @Const
  public void dontDoThis() {
    foo();
  }

  void foo () {
    d = 42;
  }
...
```

```
listener.autoload=gov.nasa.jpf.annotation.Const,...
listener.gov.nasa.jpf.annotation.Const=
                    .aprop.listener.ConstChecker
```

```
====================================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.AssertionError: instance field write within const context: int ConstViolation.d
        at ConstViolation.foo(ConstViolation.java:15)
        at ConstViolation.dontDoThis(ConstViolation.java:11)
        ...
```

jpf-aprop/src/examples/ConstViolation.jpf

Example 7: SandBox Annotation

- more sophisticated, instance aware scope property
- instances only allowed to write “owned” fields (incl. fields of objects stored in reference fields)
- mechanism suitable for security related properties

```
class X {
  int d;
  void doSomethingUnsuspicious () {
    d++; // nothing bad in and of itself
  }
...
@SandBox
class Y {
  X myOwnX = ...
  void foo (X x){
    x.doSomethingUnsuspicious();
  }
  void bar () { myOwnX.d = 42; }
...
Y y = new Y();
y.bar();          // fine
y.foo(new X()); // not so fine
```

```
listener=.aprop.listener.ConstChecker
```

```
====================================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.AssertionError: write to non-owned object: SandBoxViolation$X@290
                                     from sandbox: SandBoxViolation$Y@294
        at SandBoxViolation$X.doSomethingUnsuspicious(SandBoxViolation.java:30)
        at SandBoxViolation$Y.foo(SandBoxViolation.java:37
```

jpf-aprop/src/examples/SandBoxViolation.jpf

Example 8: Programming-by-Contract

- property annotations can be parameterized with expressions
- can be a lot more complex
- inheritance aware
- expr evaluation has no SUT side-effects

```
class Base {
  @Ensures("Result > 0")
  public int compute (int c){ return c -1; }
...
@Invariant({ "d within 40 +- 5",  "a > 0" })
public class Derived extends Base {
  double d;  int a;   // not checked until return from ctor

  ContractViolation() { a = 42;  d = 42; }

  @Requires("c > 0")
  @Ensures("Result >= 0")
  public int compute (int c){
    return c - 3;
  }

  public void doSomething (int n){
    for (int i=0; i<n; i++){
      d += 1.0;
    }
  }
...
Derived t = new Derived();
//int n = t.compute(3);  // would violate strengthening
                                            base postcondition
t.doSomething(10);  // violates 'd' invariant
```

jpf-aprop/src/examples/ContractViolation.jpf

Example 9: Overflow

- Java does not throw exceptions on overflow
- tedious to check in SUT ⇒ usually ignored

JPF configuration

```
vm.insn_factory.class =
    .numeric.NumericInstructionFactory
```

System under Test

```
void notSoObvious(int x){
  int a = x*50;
  int b = 19437583;
  int c = a;

  for (int k=0; k<100; k++){
    c += b;
    System.out.println(c);
  }
}
...
notSoObvious( 21474836);
```

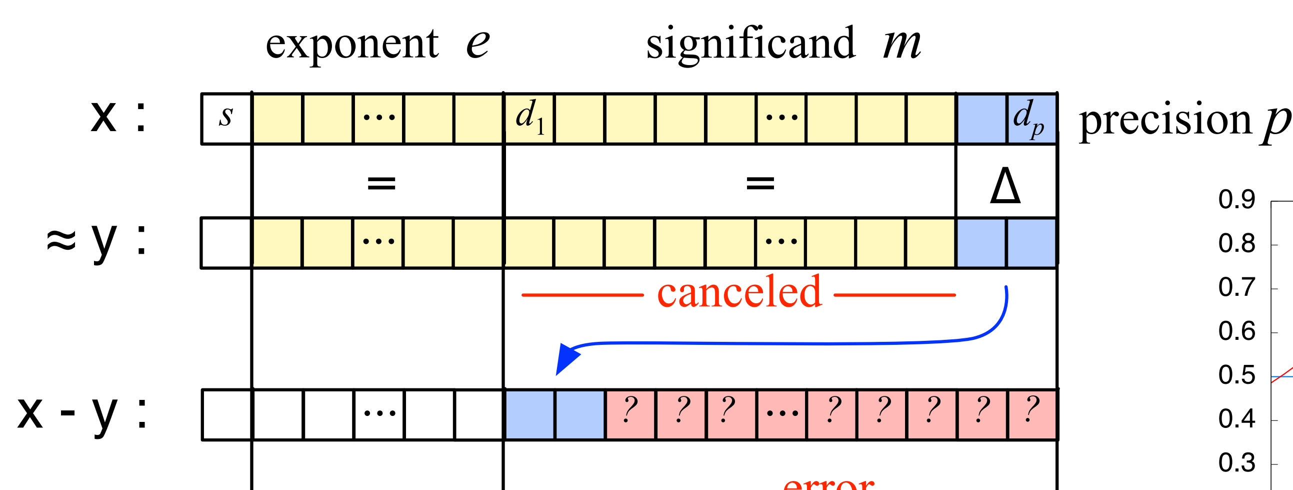
Report

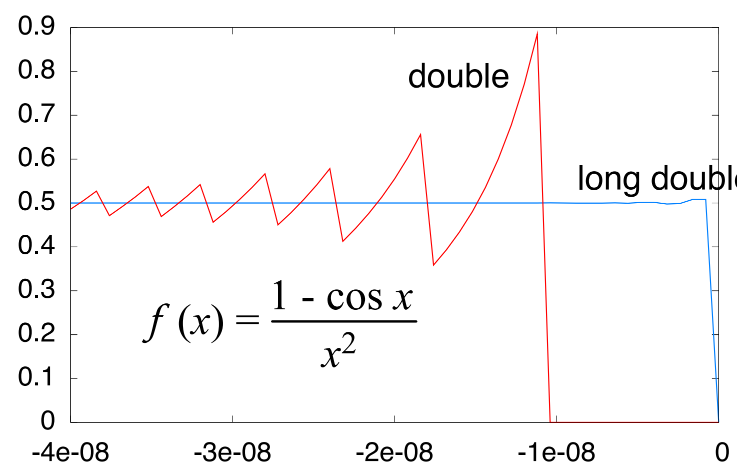
```
...
2103933699
2123371282
2142808865
...
====================================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.ArithmeticException: integer overflow: 2142808865+19437583 = -2132720848
        at Overflow.notSoObvious(Overflow.java:18)
...
```

jpf-numeric/src/examples/overflow.jpf

Example 10: Catastrophic Cancellation

- errors and required inspection can be a lot more intricate
- e.g.: amplification of previous operand errors due to cancellation of identical leading bits in the significands, followed by normalization of the result






```
double a = 77617.0;
double b = 33096.0;
res = 333.75*pow(b,6) + pow(a,2)*(11*pow(a,2)*pow(b,2) -
                    pow(b,6) - 121*pow(b,4) - 2) + 5.5*pow(b,8) + a/(2*b);
```

```
vm.insn_factory.class =
    .numeric.NumericInstructionFactory
```

```
res=-1.1805916207174113e21 (should be -0.827396...)
...
====================================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
         java.lang.ArithmeticException: cancellation of:
               -7.917111340668963E36 + 7.917111340668962E36
                      = -1.1805916207174113E21
```

jpf-numeric/src/examples/CatastrophicCancellation.jpf

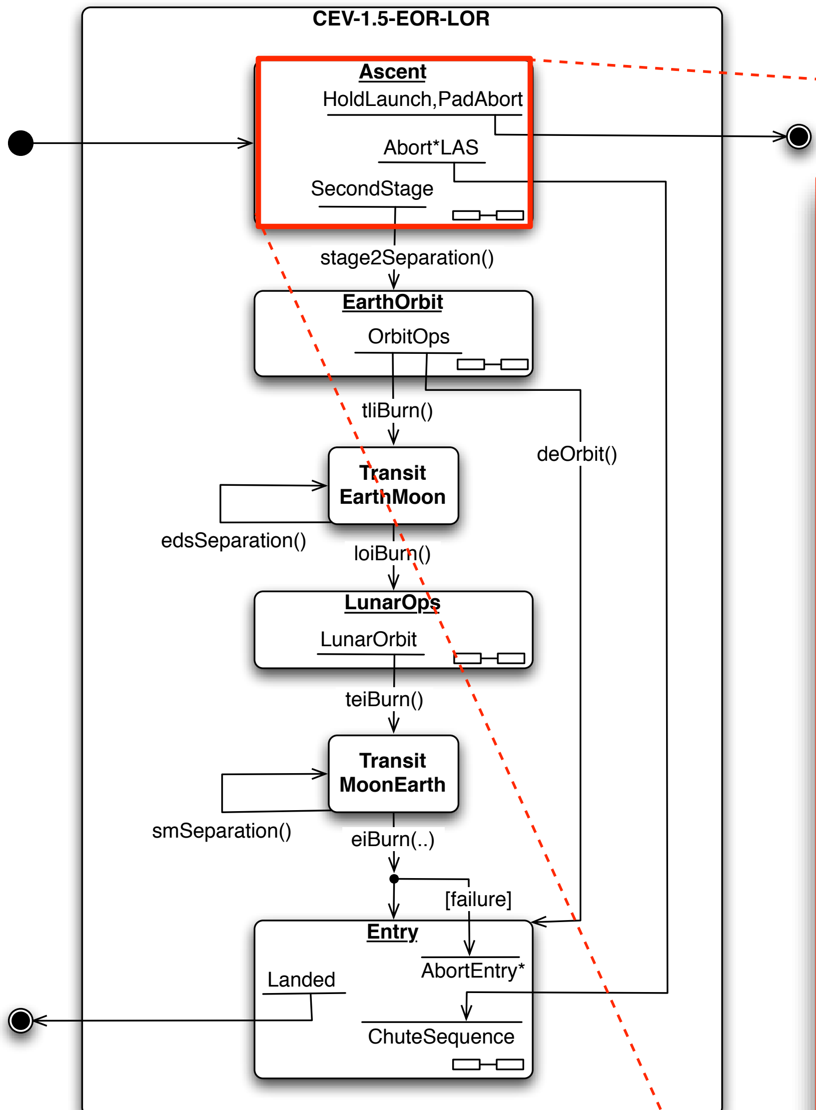
Examples: Model Verification

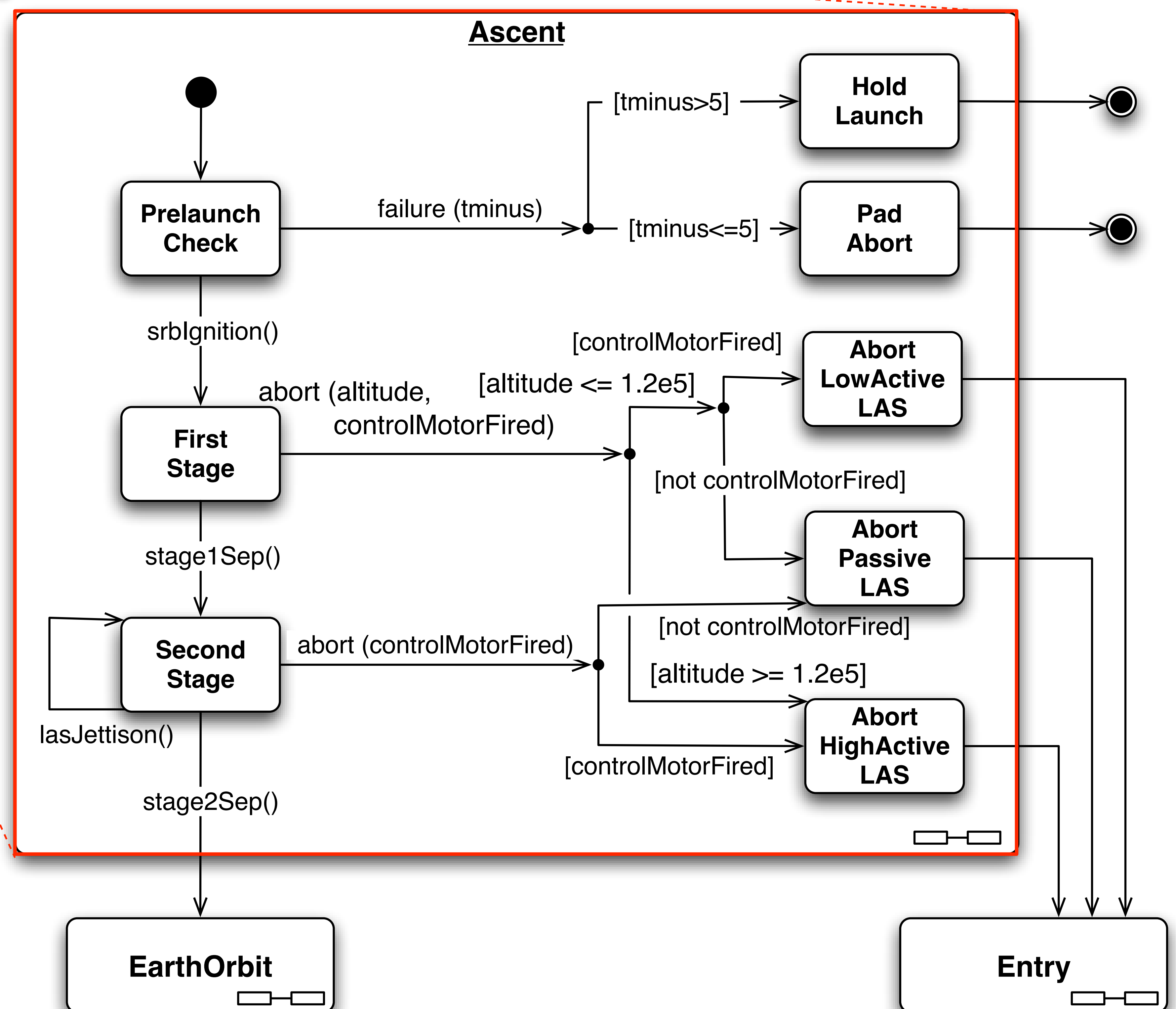
- motivation: model driven development
- as models get more complex, risk of model inconsistencies increases
- classic example: state machine verification
- usually requires translation into JPF specific model representation (application that is JPF dependent)

UML Model Checking (1)

Ames Research Center

model is understandable ..



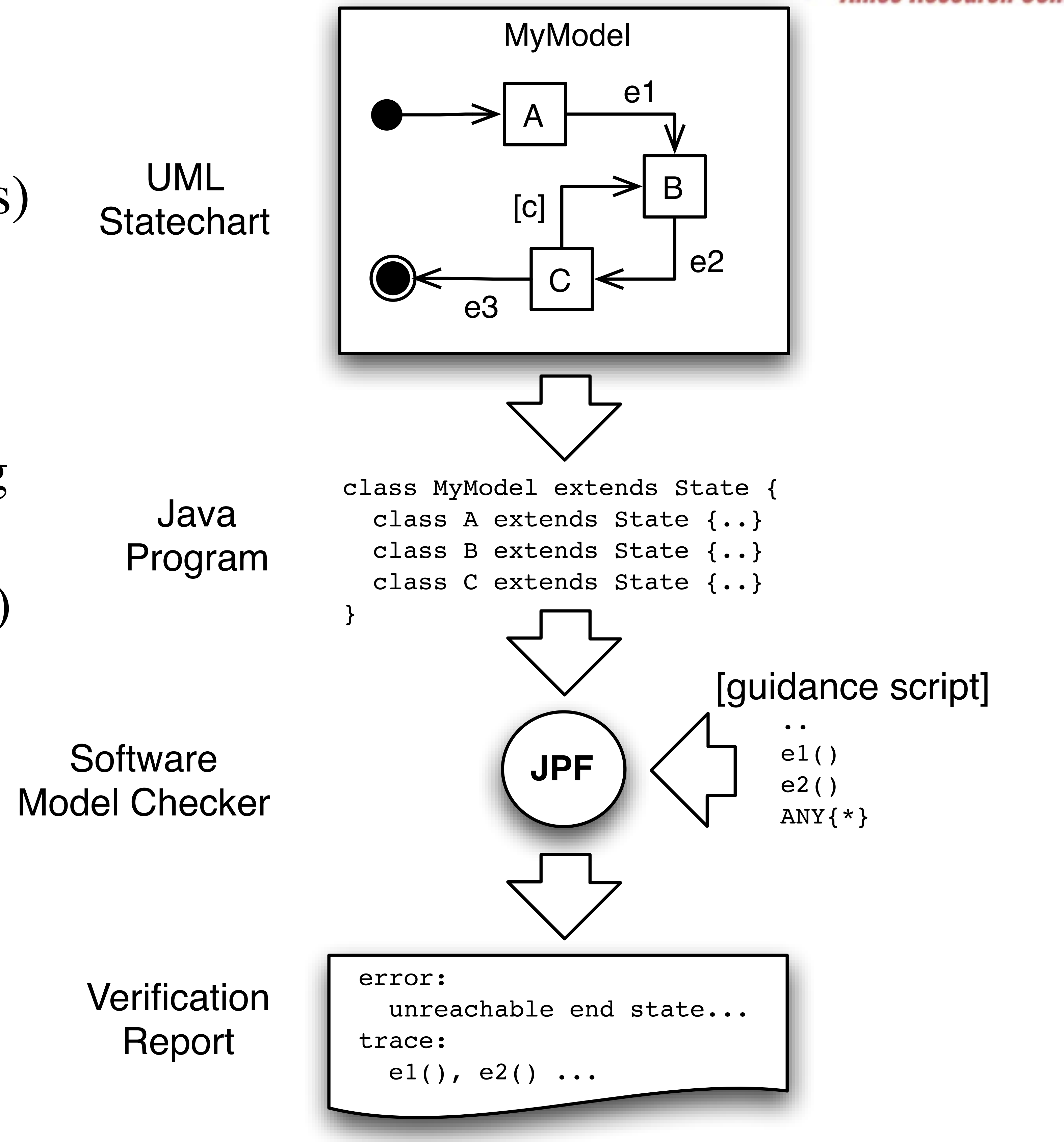


.. **but does it work?**

(actions, guards, reachability etc.)

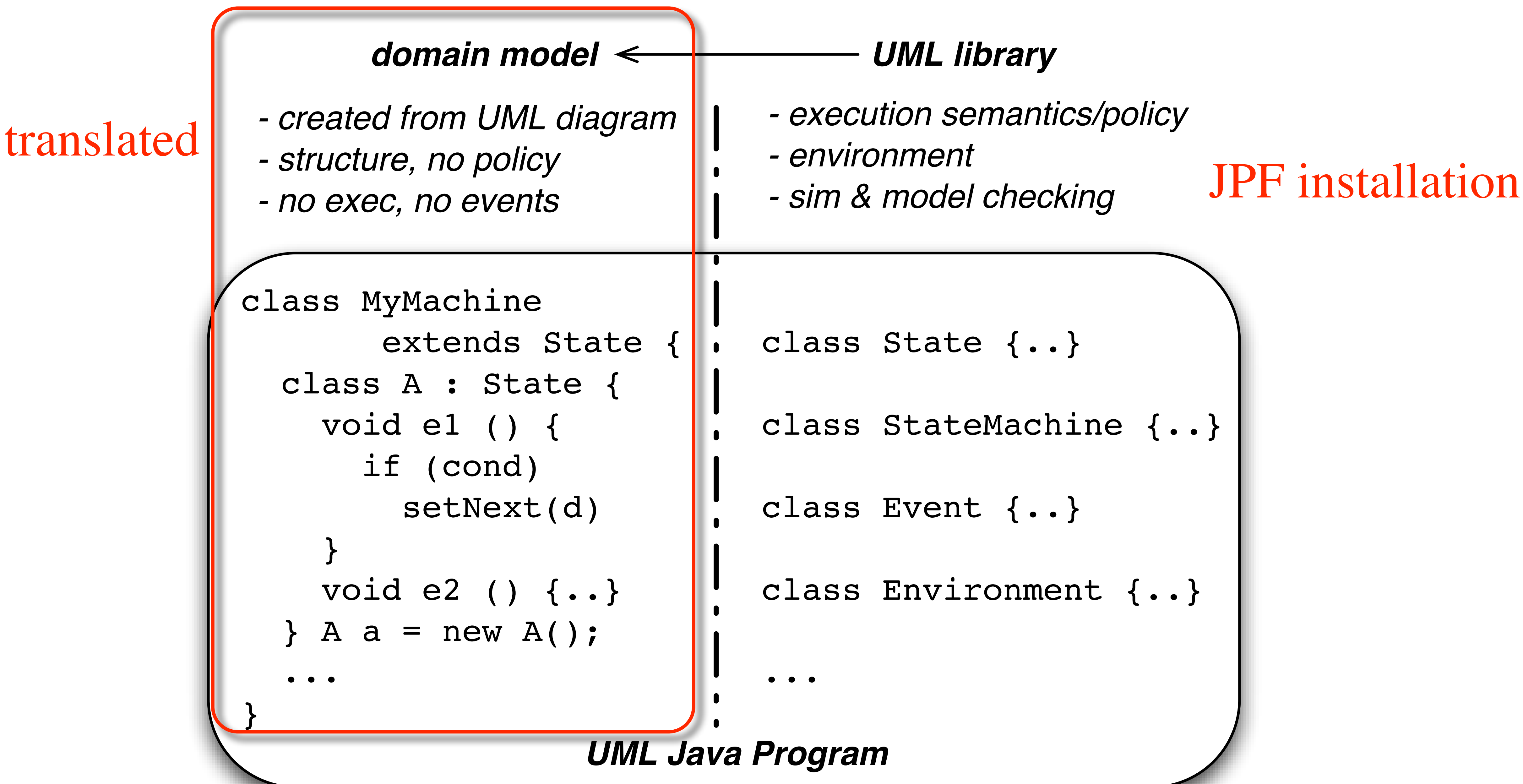
UML Model Checking (2)

- to find out:
  - make model executable (give it formal semantics) ⇒ translation
  - execute it with JPF (systematically checking all enabling events and parameter combinations)



UML Model Checking (3)

- layer 1: domain model (code translated from UML diagram)
- layer 2: UML modeling library (part of JPF distribution)
- goals: model readability, UML/program state space alignment

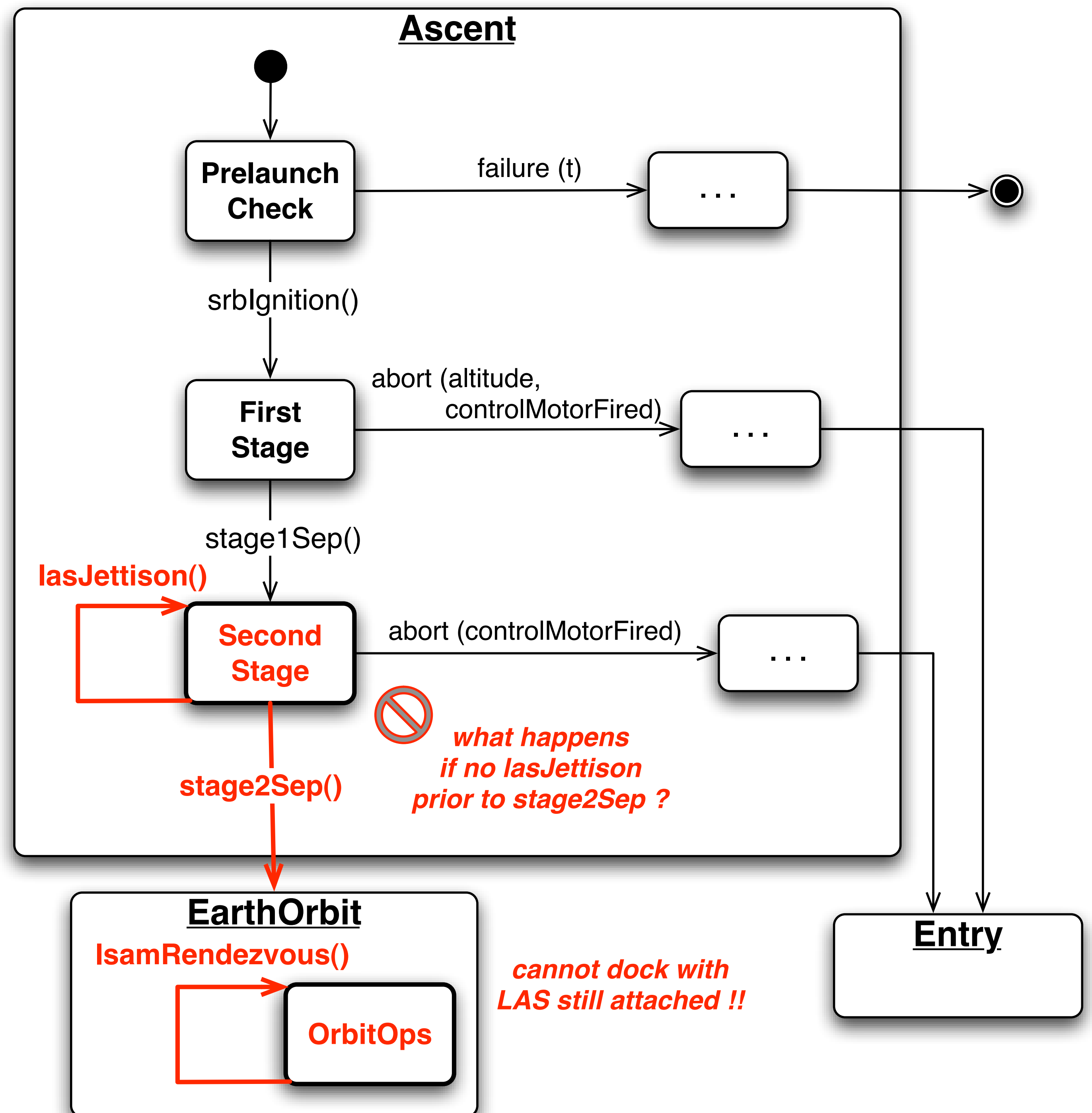


Example 11: UML Model Checking

✦ property: *"no unhandled exceptions"*

```
class OrbitOps {..
  void lsamRendezvous(){..
    assert !spacecraft contains(LAS):
       "lsamRendezvous with LAS attached"
       ..
  } ..
}
```

```
…
 =========== error #1
 NoUncaughtExceptionsProperty
 AssertionError:
    lsamRendezvous with LAS attached
   at …
=========== choice trace #1
srbIgnition()
stage1Separation()
stage2Separation()
lsamRendezvous()}
```



jpf-statechart/src/examples/jpfESAS/CEV_15EOR_LOR-las.defect.jpf

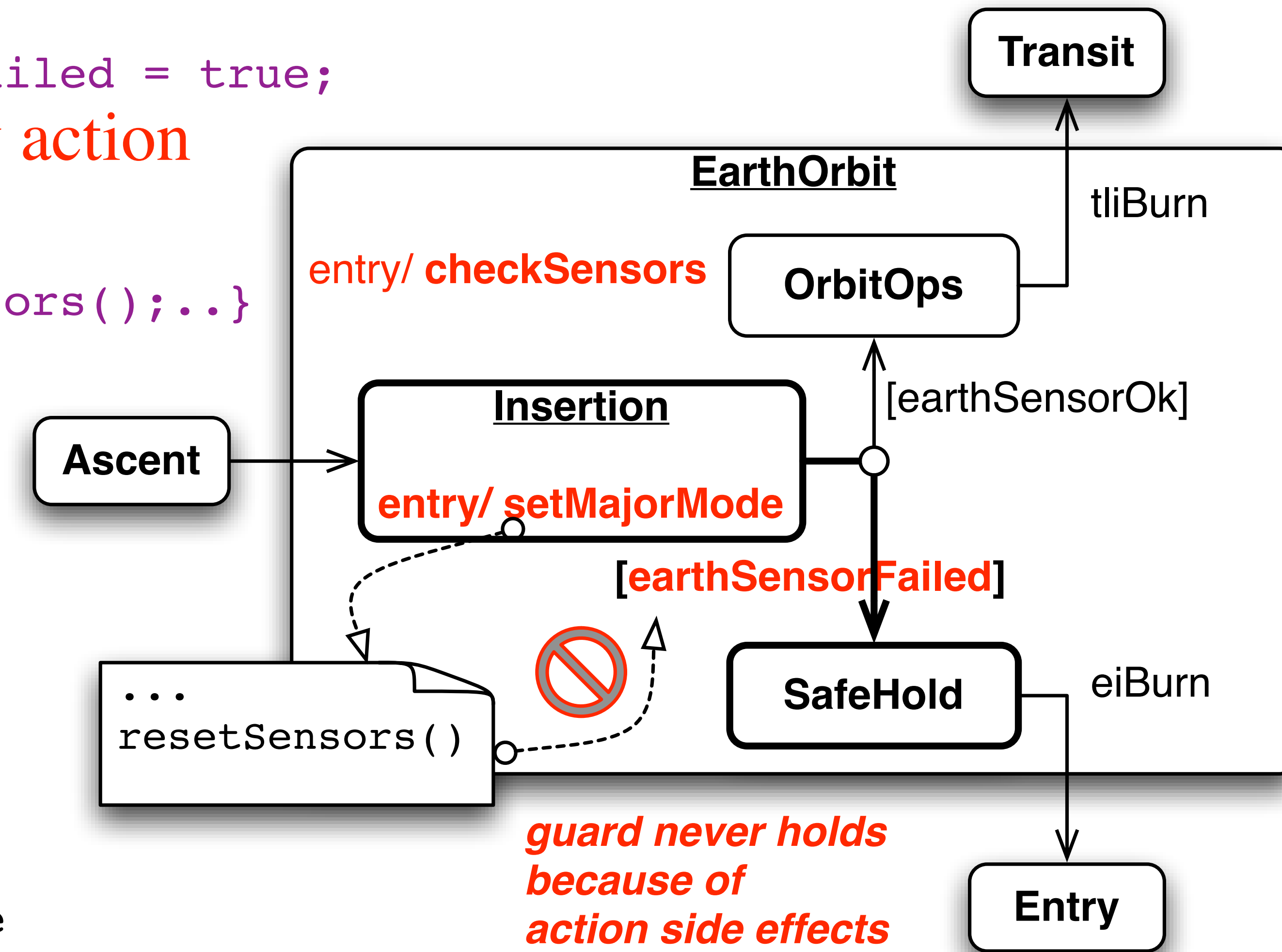
Example 12: UML Model Checking

- property: *“all states of the model have to be reachable”*

```
class EarthOrbit {..
  void entry_checkSensors() {..
    if (!checkEarthSensor()) earthSensorFailed = true;

  class Insertion {..

    void entry_setMajorMode() {..resetSensors();..}

    void resetSensors() {..
      earthSensorFailed = false; }

    void completion() {
      if (earthSensorFailed)
        setNextState(safeHold);
      ..
  }
}
```

autom. entry action

never holds




```
listener=.tools.sc.Coverage
sc.required=earthOrbit
```

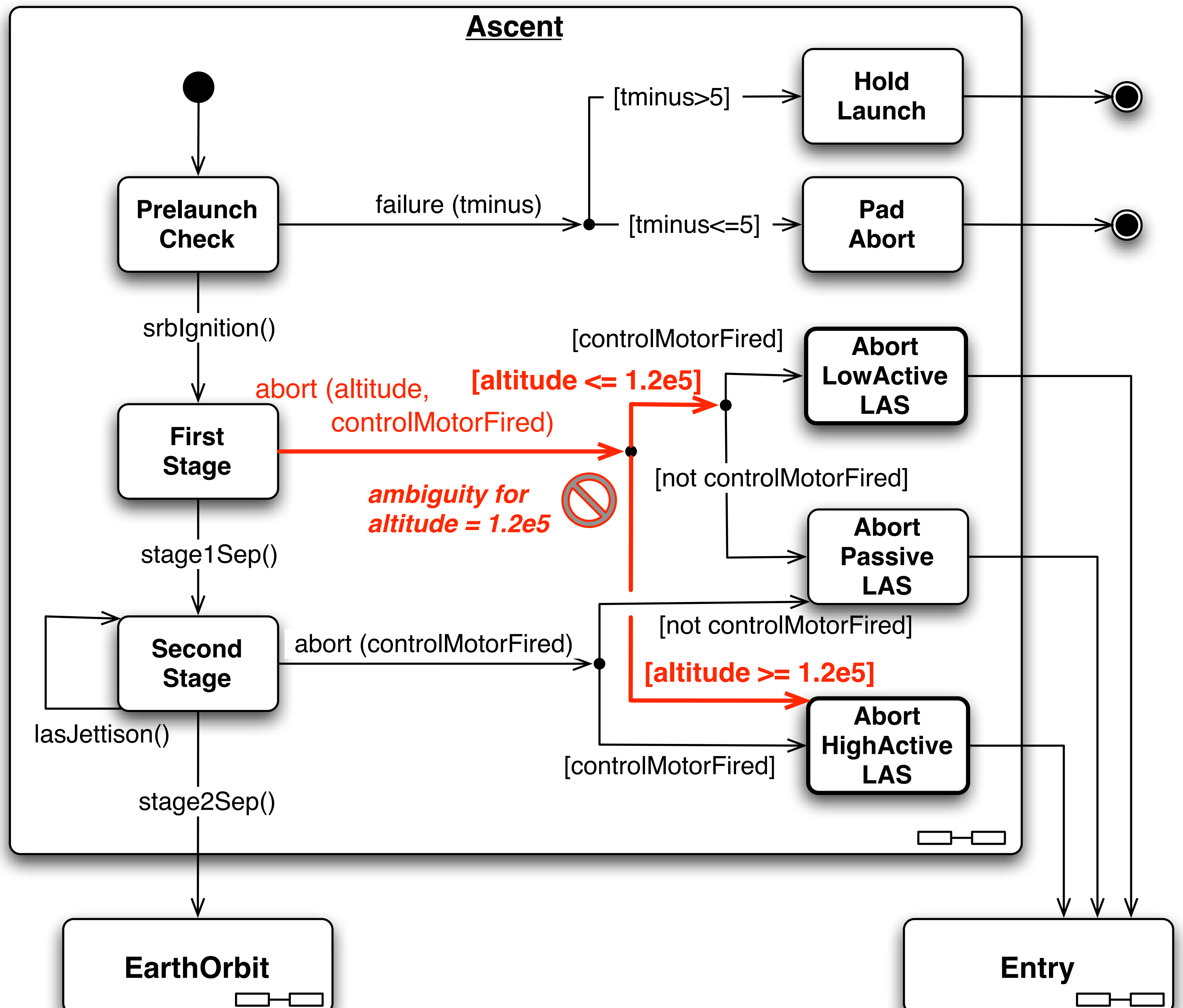
```
…
======================================= error #1
gov.nasa.jpf.tools.sc.Coverage
required  earthOrbit.safeHold NOT COVERED
…
```

jpf-statechart/src/examples/jpfESAS/CEV_15EOR_LOR-safehold.jpf

Example 13: UML Model Checking

- property: "*no ambiguous transitions*"
- example: overlapping guard conditions

```
@Params("5000|120000|200000,..")
void abort(altitude,..){..
   if (altitude <= 1.2e5)
      setNextState(abortLowActive)
...
   if (altitude >= 1.2e5)
      setNextState(abortHighActive)
```




```
============ error #1 ...
AssertionError:
ambiguous transitions in:
                ascent.firstStage
processing event: abort(120000,true)
   state 1: ascent.abortHighActiveLAS
   state 2: ascent.abortLowActiveLAS
...
=========== choice trace #1
srbIgnition()
abort(120000,true)
```

jpf-statechart/src/examples/jpfESAS/CEV_15EOR_LOR-ascent-guards.jpf

Examples: Test Case Generation

- test creation is very expensive - how many tests do we need (instruction coverage, branch coverage, MCDC, path coverage ..)
- the application for *symbolic execution*
- "normal" verification - use data to find out which paths to explore
- problem with huge input spaces (what test data is interesting?)
- symbolic execution uses opposite direction - use program structure to deduce which data values need to be tested to reach interesting program locations (exceptions, coverage requirements)

Test Case Generation (1)

- how do we identify interesting parameter values if they are not known a priori (example 13 @PARAMS annotation)?

```
@PARAMS(5000|120000|200000)

void abort(altitude){
   ...
   if (altitude <= 1.2e5)
      setNextState(abortLowActive)
   ...
   if (altitude >= 1.2e5)
      setNextState(abortHighActive)
```

- answer: test case generation with *Symbolic Execution*

Test Case Generation (2)

Program Control Structure

```
if (x > C) {
  ...
  if (y < D) {
    ...
    ...
      if (x >= y) {
        ...
      } else {

...
```

? how do we get here ?

Symbolic Execution

Path Conditions

PC_1: $(x > C)$

PC_2: $(y < D)$

⋮

PC_n: $\neg(x \geq y)$

$PC_1 \wedge PC_2 \wedge \ldots \wedge PC_n = \text{true}$

constraint solver

[x=.., y=..] — concrete test vector(s)

∅ — unreachable code

? — program logic too complex ?

Example 14: Symbolic Execution

- look for instruction that constitutes property violation and compute data that leads to it

```
void abort(altitude,controlMotorFired){
  ...
  if (altitude <= 1.2e5)
     setNextState(abortLowActive)
  ...
  if (altitude >= 1.2e5)
     setNextState(abortHighActive)
```

```
vm.insn_factory.class =
  gov.nasa.jpf.symbc.SymbolicInstructionFactory
symbolic.method = ..abort(sym#con)
...
```

```
symbolic.dp=choco
Symbolic Execution Mode
...
***Execute symbolic INVOKEVIRTUAL: abort(IZ)V
                        (altitude_1_SYMINT, controlMotorFired_CONCRETE )
...
Property Violated: PC is # = 2
altitude_1_SYMINT[120000] >= CONST_120000 &&
altitude_1_SYMINT[120000] <= CONST_120000
...
Property Violated: result is  "java.lang.AssertionError: ambiguous transitions
in: ascent.firstStage..."
...
====================================================== Method Summaries
Symbolic values: altitude_1_SYMINT
abort(120000,true)  --> "java.lang.AssertionError: ambiguous transitions in:
                         ascent.firstStage..."
```

jpf-statechart/src/examples/jpfESAS/CEV_15EOR_LOR-ascent-guards-symbolic.jpf

Example 15: Test Case Generation

- Symbolic Execution especially suitable to generate test suite to achieve path coverage

```
public class TestPaths {
  ...
  // what tests do we need to cover all paths?
  public static void testMe (int x, boolean b) {
    if (x <= 1200){
      // BLOCK-1
    }
    if(x >= 1200){
      // BLOCK-2
    }
  }
}
```

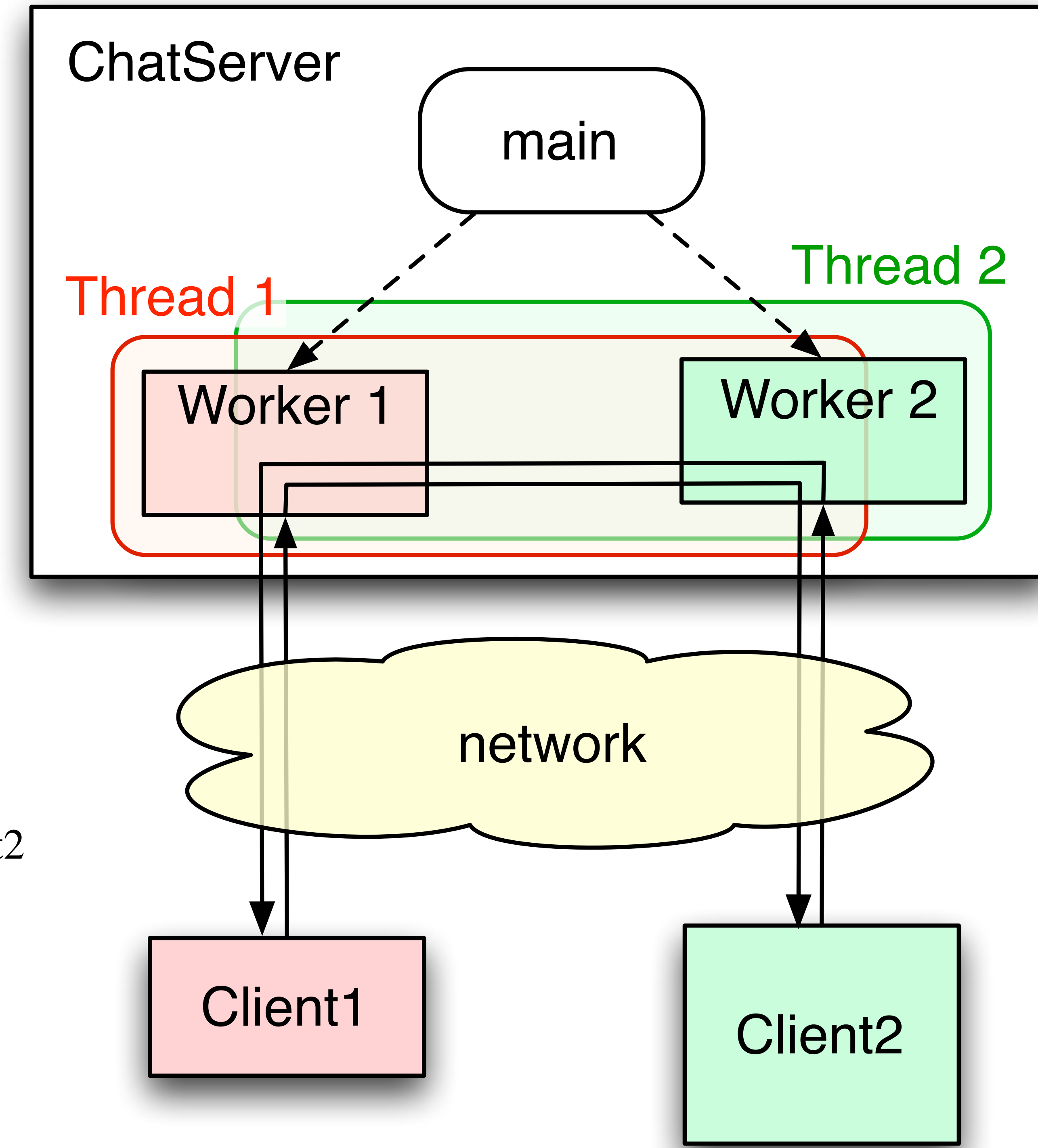
```
vm.insn_factory.class =
    .symbc.SymbolicInstructionFactory
symbolic.method= TestPaths.testMe(sym#con)
listener = .symbc.SymbolicListener
```

```
...
***Execute symbolic INVOKESTATIC: testMe(IZ)V  ( x_1_SYMINT, b_CONCRETE )
..
PC # = 2
x_1_SYMINT[1200] >= CONST_1200 &&
x_1_SYMINT[1200] <= CONST_1200
...
x_1_SYMINT[-1000000] < CONST_1200 &&
x_1_SYMINT[-1000000] <= CONST_1200
...
====================================================== Method Summaries
...
testMe(1200,true)         BLOCK-1, BLOCK-2
testMe(-1000000,true)     BLOCK-1
testMe(1201,true)                  BLOCK-2
```

jpf-symbc/src/examples/TestPaths.jpf

Examples: Distributed Applications

- example: ChatServer
- 1 ChatServer process
- N Client processes
- server creates one worker object/thread per connection



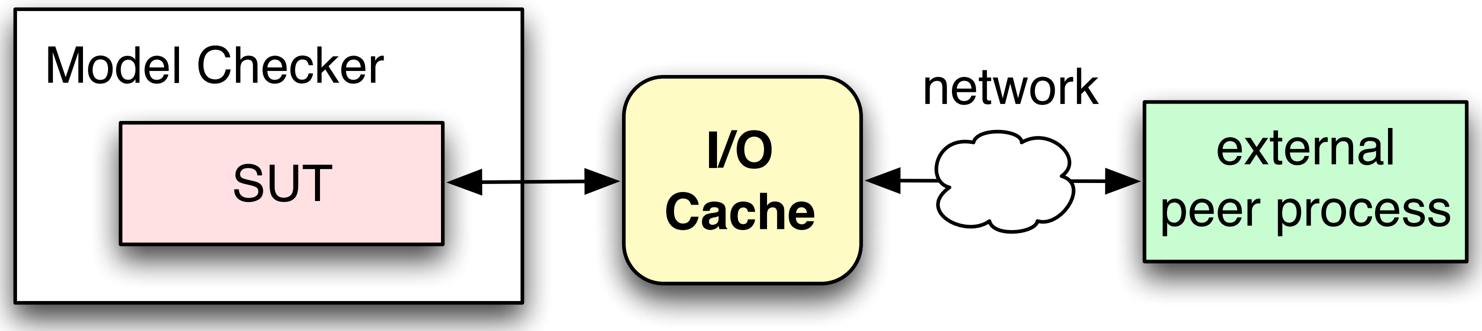
- model checking problem:
  - state explosion for known clients:

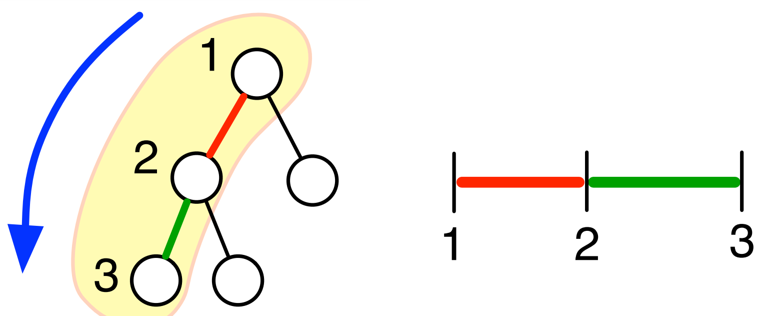
    $$S_{total} = S_{server} \times S_{client1} \times S_{client2}$$

  - what to do if clients unknown ?

IO Cache

- no stubs required
- environment executes normally
- protocol structure preserved

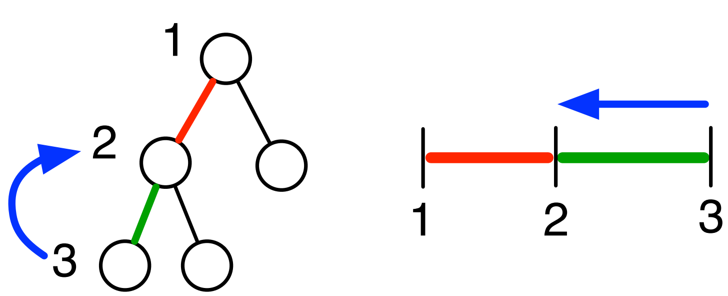




new state: store I/O data streams "globally"

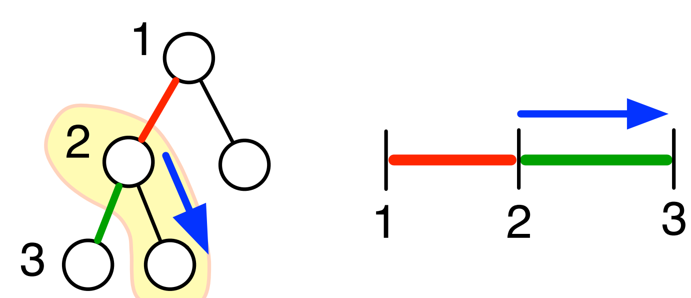
cache I/O data & message size

map program state to stream position



backtracking: restore I/O state "locally"

reset streams back to old state



continue: replay previous I/O

duplicate sends: ignore

duplicate reads: previous peer response

Example 16: ChatServer Deadlock

- jpf-net-iocache finds server defect (deadlock) without analyzing clients

```
listener=.network.listener.CacheNotifier,
         .network.listener.CacheLogger
```

```
...
[SEVERE] unprotected field access
  of ChatServer.workers
  in thread: Thread-1..
...
Client quit, 1 client(s) left.
Client quit, 1 client(s) left.

============================== error #1
gov.nasa.jpf.jvm.NotDeadlockedProperty
deadlock encountered:
  thread index=0,name=main,status=WAITING..
  thread index=1,name=Thread-0,status=TERMINATED..
  thread index=2,name=Thread-1,status=TERMINATED..

============================== snapshot #1
thread index=0,name=main,status=WAITING...
  waiting on: gov.nasa.jpf.network.chat.ChatServer@294
  call stack:
    at gov.nasa.jpf.network.chat.ChatServer.accept(ChatServer.java:85)
    ...
```

```
class Worker implements Runnable {
  ...
  public void run() {
    ..server.remove(id)
  ...

class ChatServer {
  ...
  void remove(int n) {
    workers[n] = null;
    activeClients--;
    synchronized (this){
      notify();
    }
    ...

  void accept(int maxServ, int port) {
    ...
    synchronized (this) {
      while (activeClients != 0) {
        try {
          wait();
      ...
```

jpf-net-iocache/src/examples/../chat/ChatServerBug.jpf

Using JPF

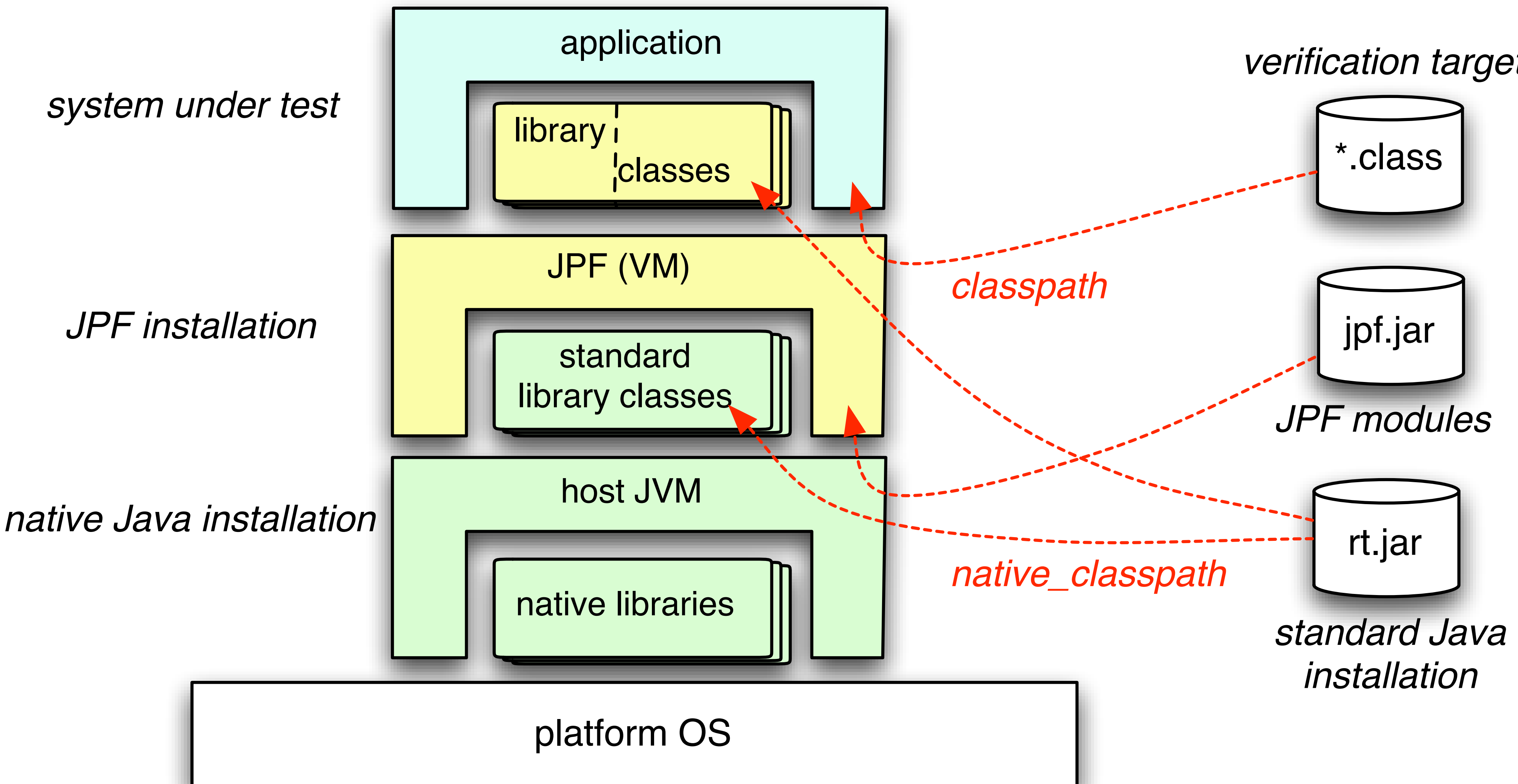
- obtaining JPF
- installing, building and testing JPF
- JPF configuration
- running JPF
- JPF and NetBeans
- JPF and Eclipse

Extending JPF

- Basics
  - a VM running inside a JVM
  - JPF Components
  - JPF directory structure
  - JPF runtime structure
- Extension Mechanisms
  - Search Policies
  - ChoiceGenerators
  - Listeners
  - Bytecode Factories
  - Model-Java-Interface and Native Peers
  - Attributes

Basics: a VM running inside JVM

- verified Java program is executed by JPF, which is a virtual machine implemented in Java, i.e. runs on top of a host JVM
  ⇒ easy to get confused about who executes what



Wednesday, February

Conclusions

- check out http://babelfish.arc.nasa.gov/trac/jpf
- all answers will be there (eventually)
- .. if not - try http://groups.google.com/group/java-pathfinder
- if not - we are here to help: Peter.C.Mehlitz@nasa.gov