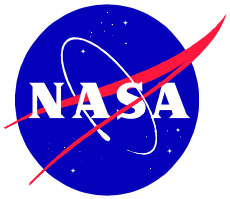

JPF for Beginners

David Bushnell

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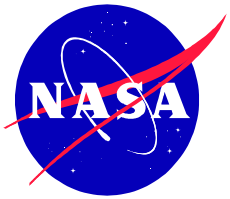
JPF Workshop 2008

What is JPF?

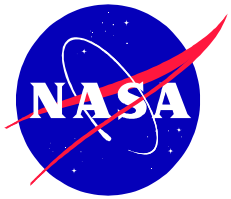
- An *explicit state model checker*
  - Focus is on finding bugs in Java programs
- A *framework* for runtime Java verification
  - Model checking
  - Symbolic execution
  - UML state chart modeling
  - Numeric Verification (int overflow, fp over/underflow, …)
  - ... *ad infinitum*

What is Model Checking?

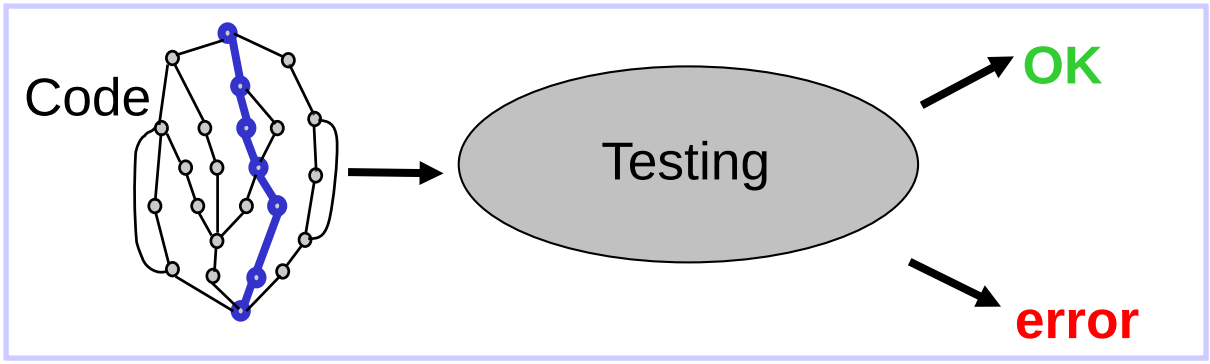


- Systematically verifying that a model satisfies a set of properties
  - Formal Model: UML state charts, Java programs, Promela models, …
  - Properties: Temporal Logic (xTL), code assertions, …
- In JPF:
  - The models are Java programs
  - The properties can be assertions, gov.nasa.jpf.Property objects, or JPF listener objects

Model Checking vs Testing

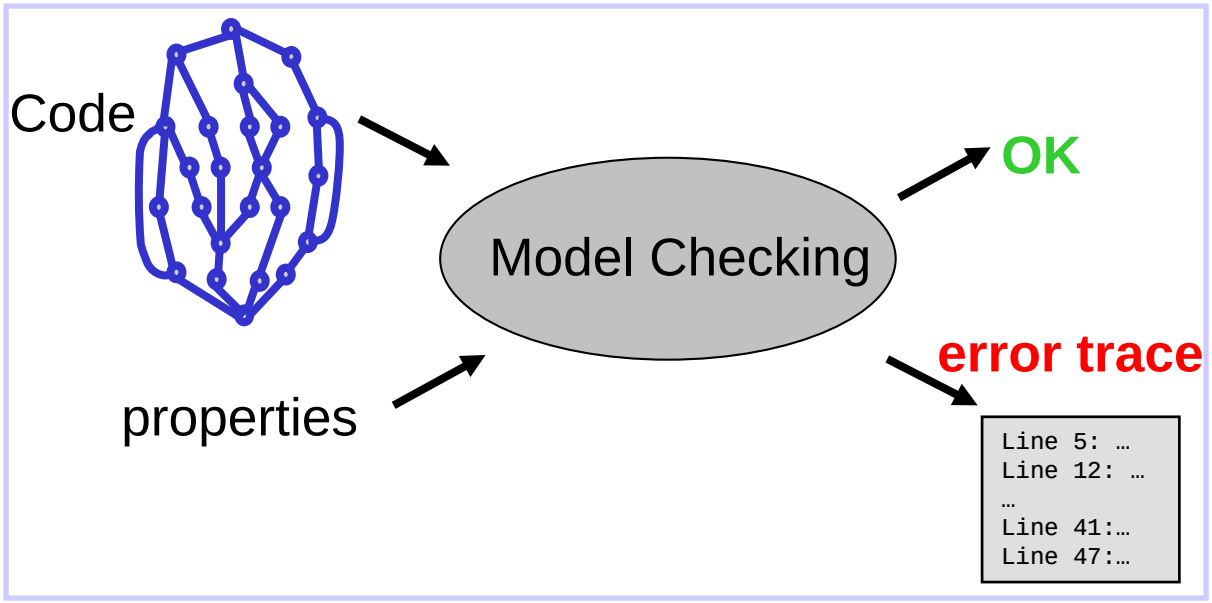


- A test will explore a single execution path
  - *You* must identify each important execution path
  - *You* must find the inputs that will execute those paths.



Model Checking vs Testing

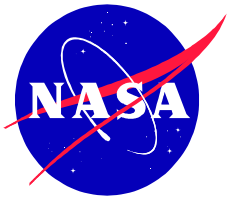
- A model checker can explore every execution path
  - Including scheduler decisions for concurrent models
- A model checker can identify both errors and the execution paths leading to those errors



What Can JPF Handle?

- Pure Java up to ??-KLOC
  - Depends on logical complexity and state size, not KLOC.
  - Programs with 100K+ lines have been analyzed
- Multi-threaded code (*Of Course!*)
- Can find: deadlocks, race conditions, unhandled exceptions, application-specific assertions, ...

What Can't JPF Handle?



- *Unsupported* native calls (JNI)
  - Can simulate/support native calls with MJI
- Hence: No libraries with unsupported native calls
  - Much or all of java.io, java.net, AWT, Swing, …
- Really complex programs
  - But: it is often enough to apply JPF to a simplified version, AKA a *model*.
  - Example: apply JPF to a communications protocol used in your program

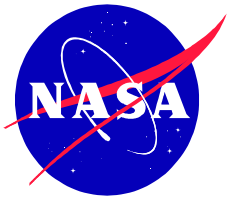
Using JPF

- Installing JPF
- Using JPF in an Eclipse project
- Configuring JPF
- Common Config Options
  - Example: Running JPF, detecting race conditions
- Controlling JPF Execution
  - Example: Detecting deadlock
- Extensions
- Listeners
  - Example: OpCodePrinter
- Overriding Bytecodes
  - Example: Numerics

Installing JPF for Eclipse

- Not covered: using JPF with other IDEs or from the command line
  - See documentation at SourceForge
- Prerequisites:
  - JDK 1.5+
  - Eclipse 3.2+ (www.eclipse.org)
  - Subclipse plugin (subclipse.tigris.org)

Installing JPF for Eclipse (2)

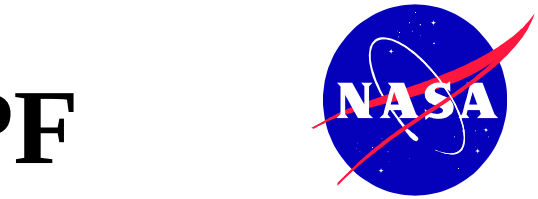


- Downloading JPF in Eclipse:
  - Create a new project (*not* a Java project)
  - Use the SVN → "Checkout Projects from SVN" wizard
  - Repository URL:
    https://javapathfinder.svn.sourceforge.net/svnroot/javapathfinder
  - Select "trunk" as your folder, *not* "tags" or "branches"
  - Anything for project name
  - Use defaults for everything else
  - Can have many copies of JPF, each as a different Eclipse project

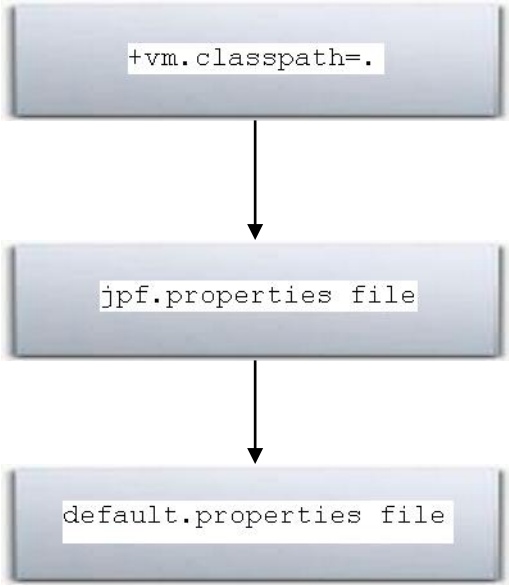
Configuring JPF

- **Bad News**: JPF has *lots* of config options
- **Good News**: The defaults are mostly ok. You seldom need to set more than 4 or 5.

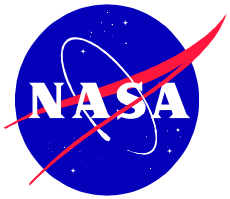
Configuring JPF



- Config hierarchy:
  - Command line args
    (written as **`+vm.classpath=.`**)
    take precedence over
  - jpf.properties values
    (written as **`vm.classpath=.`**)
    take precedence over
  - default.properties values
- Command line trick: comment out config options with **`+_some.config.option=...`**



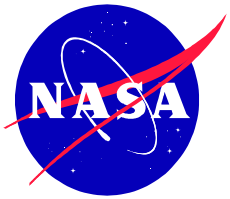
Configuring JPF (2)



- Rules:
  - *Never change* default.properties
  - jpf.properties is for values common to a project. Copy it to your project's top-level directory and change your copy

    (*do not change* the jpf.properties file in your JPF project)
  - Set the command line args for values specific to a single run
- In practice, in Eclipse:
  - Ignore jpf.properties.
  - Set everything with the command line using Eclipse's launch configurations
- For details on most core config properties, look in default.properties and jpf.properties

Configuring JPF (3)



- Common config properties
  - jpf.basedir
    - Where JPF is located
  - vm.classpath
    - Where your compiled code is located, a classpath.
    - Usually set to “.”, i.e. **`vm.classpath=.`**
  - vm.sourcepath
    - Where your source code is located.
    - Defaults to **`vm.classpath`**, so you don’t usually need to set it
  - search.class
    - The search strategy to use (a class).
    - Defaults to **`gov.nasa.jpf.search.DFSearch`**
    - Look in **`src/gov/nasa/jpf/search`** for others

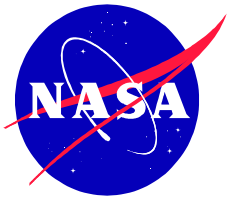
Configuring JPF (4)

- Some other common config properties
  - vm.storage.class
    - Class used to hash/store states (if not set, states are not matched)
    - For small problems, can set to empty,
      `vm.storage.class=`
  - search.multiple_errors
    - **true/false:** Quit after the first error or keep going?
  - jpf.report.xxx
    - Lots of options to configure the reporting subsystem
      See default.properties
    - jpf.report.console.finished
      - What to report when JPF exits. Defaults to some statistics.
    - jpf.report.console.show_code
      - **true/false:** Show the bytecode in error traces?
  - jpf.listener
    - A "**:**" separated list of Listener classes

Using JPF in Eclipse

- Create an Eclipse Java project
- Write your Java code
- Create an Eclipse run configuration that:
  - Has **`gov.nasa.jpf.JPF`** as its “Main class”
  - Has the right JPF config args
  - Has your JPF project in its classpath

Running JPF Race Detection

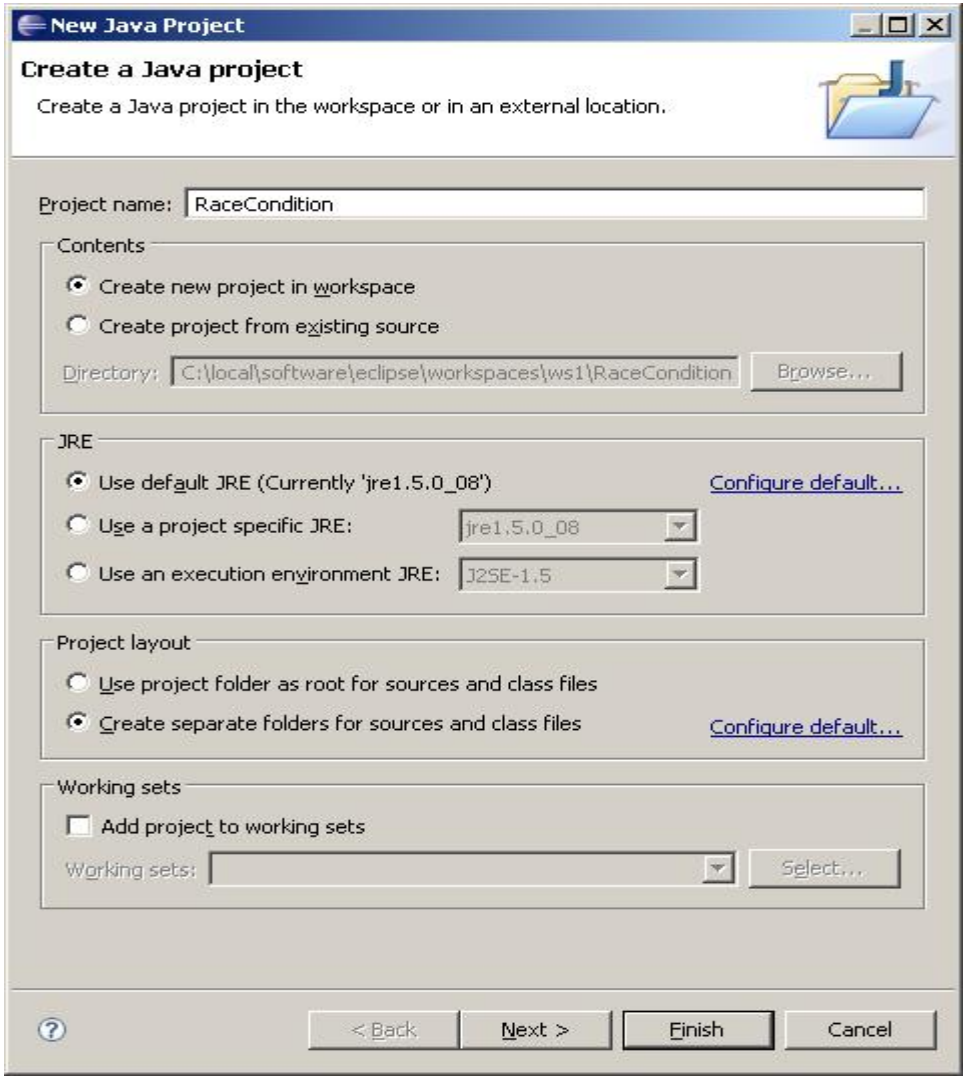


DEMO

MyRaceCondition

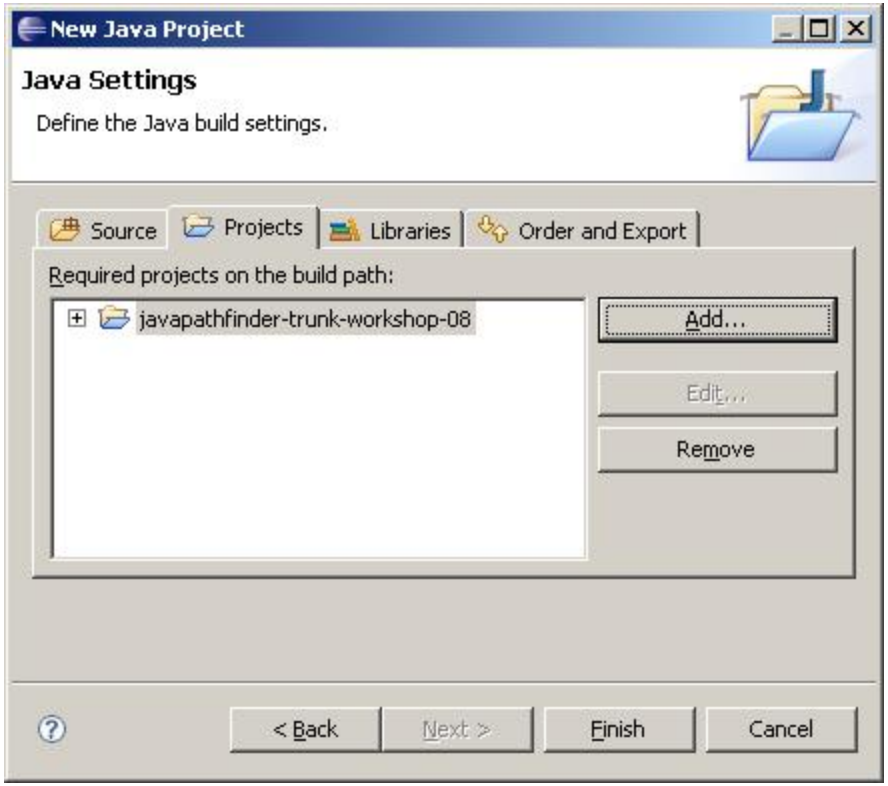
Create an Eclipse Project (1)

- Create a Java Eclipse project

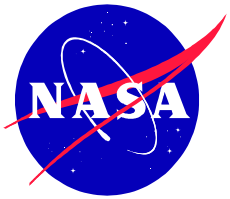


Create an Eclipse Project (2)

- Add your JPF project to the Java build settings



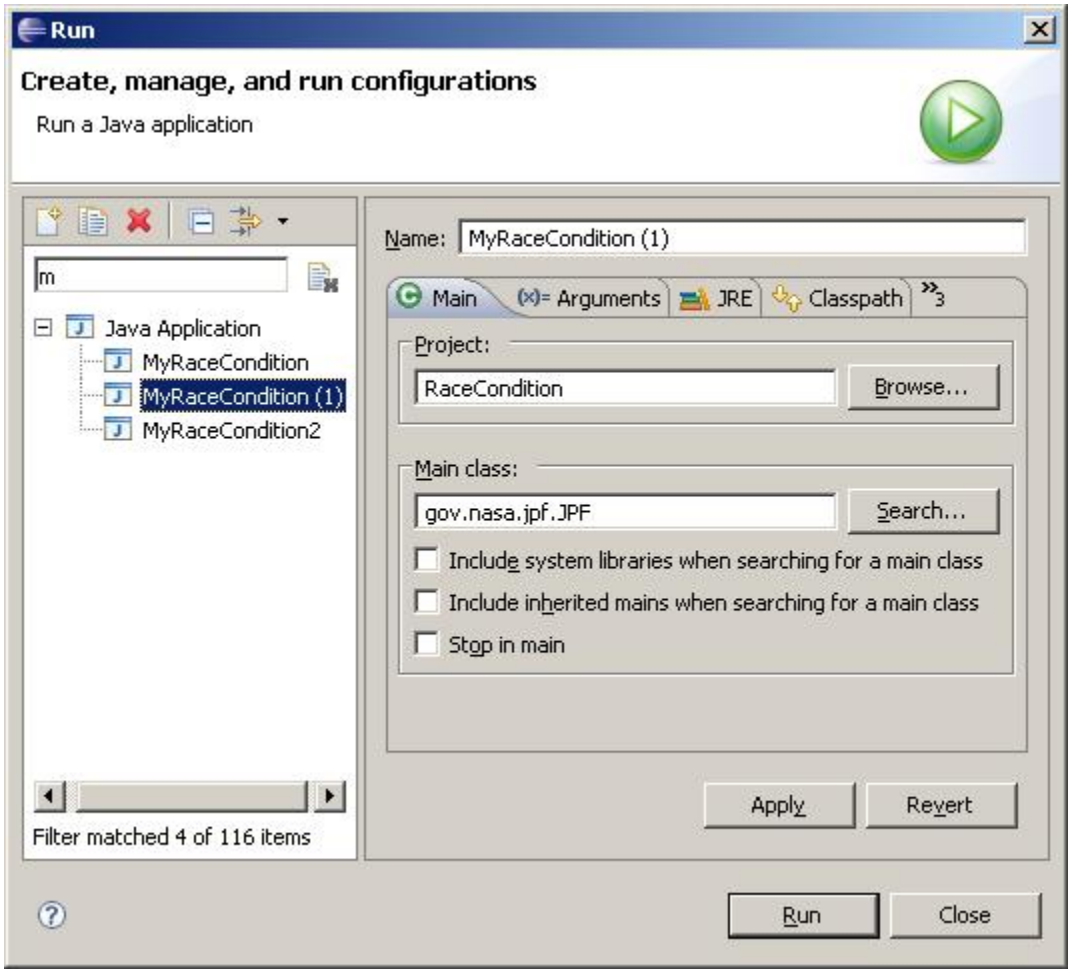
Write Your Java Code




```
public class MyRaceCondition {
  private static class Pair {
    String x = "x";
    String y = "y";

    public void update() {
      x = x + y + x;
    }
  }


  private static class RC extends Thread
    {
    Pair p;

    public void run() {
      p.update();
    }
  }

    public static void main(String[] args) {
      Pair p = new Pair();
      RC rc1 = new RC();
      RC rc2 = new RC();

      rc1.p = p;
      rc2.p = p;

      rc1.start();
      rc2.start();
      rc1.join();
      rc2.join();
      System.out.println("x: " + p.x);
    }
}
```

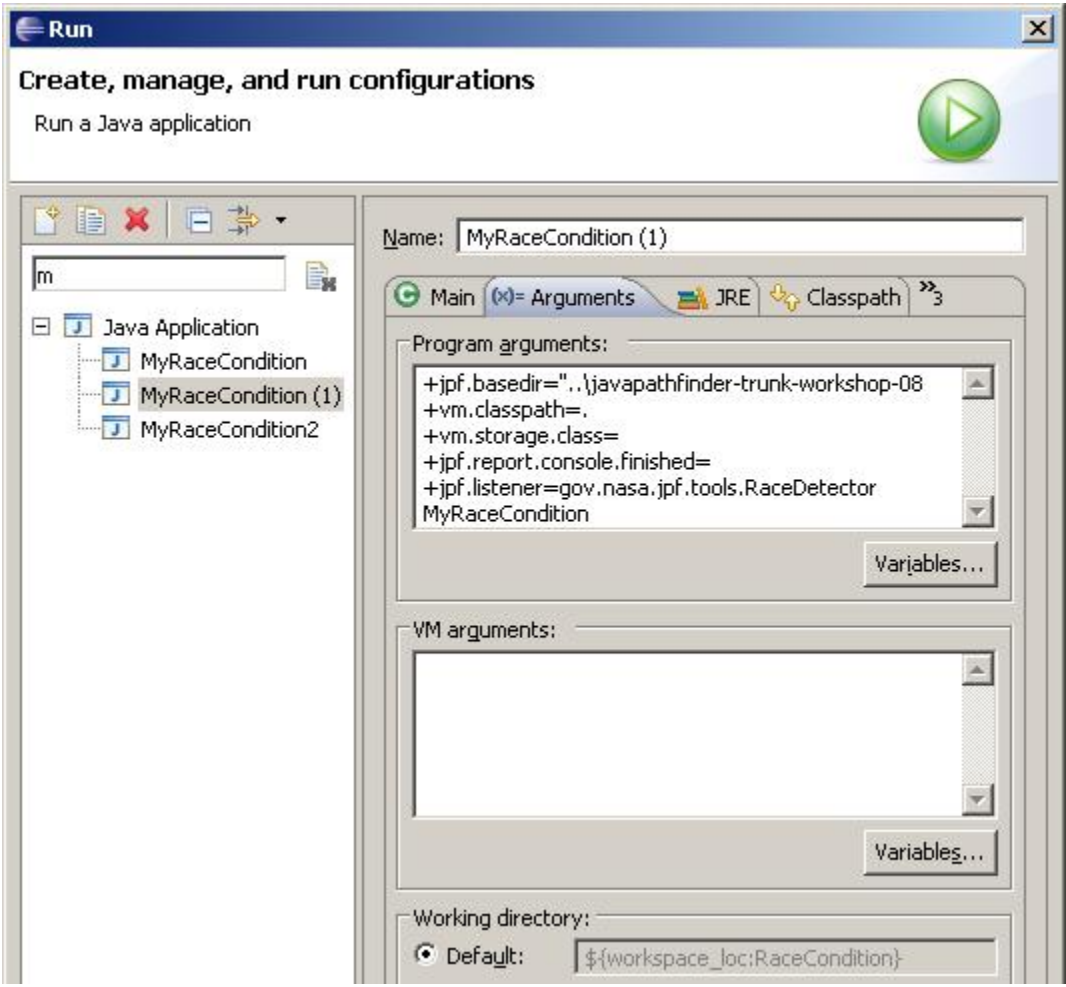
Create Eclipse Run Config (1)

- **`gov.nasa.jpf.JPF`** is the Main class



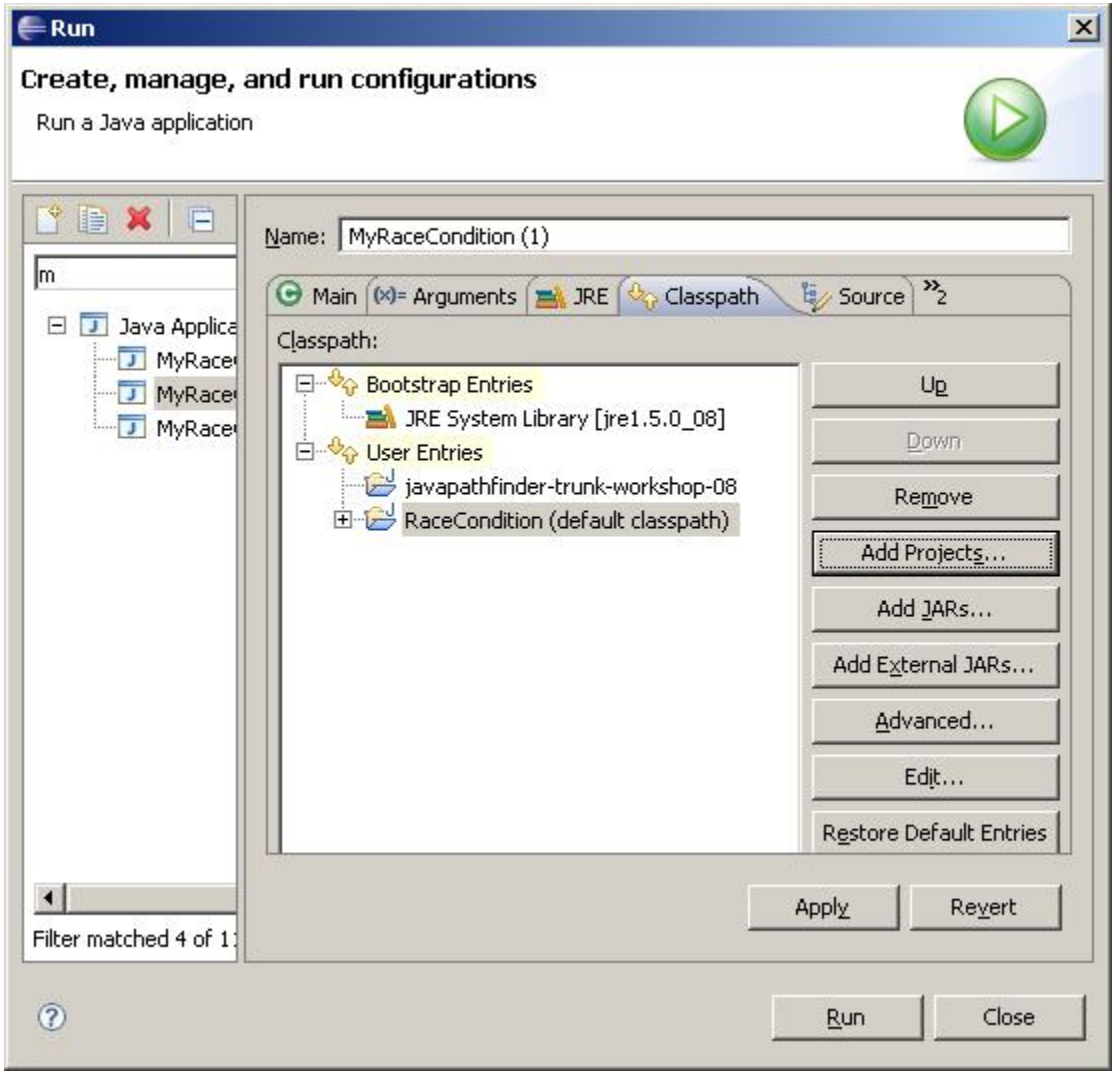
Create Eclipse Run Config (2)

- Set your arguments
- For race conditions: `jpf.listener=...RaceDetector`
- Last arg should be the class you are checking

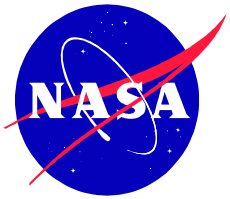


Create Eclipse Run Config (3)

- Add your JPF project in the Classpath tab
- Run



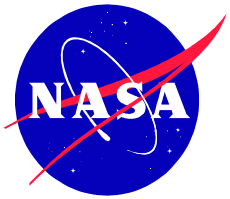
Race Detection Results



Results:

```
potential race detected: MyRaceCondition$Pair@216.x
    read from thread: "Thread-1", holding locks {} in
    MyRaceCondition$Pair.update(MyRaceCondition.java:7)
    write from thread: "Thread-0", holding locks {} in
    MyRaceCondition$Pair.update(MyRaceCondition.java:7)

============================================================ error #1
gov.nasa.jpf.tools.RaceDetector
potential field race: MyRaceCondition$Pair@216.x
... etc ...
------------------------------------------------------------ transition #9 thread: 1
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>Thread-0,Thread-1}
  MyRaceCondition.java:7          : x = x + y + x;
  MyRaceCondition.java:8          : }
  MyRaceCondition.java:16         : }
... etc ...
------------------------------------------------------------ transition #11 thread: 2
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {main,>Thread-1}
  MyRaceCondition.java:15         : p.update();
------------------------------------------------------------ transition #12 thread: 2
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {main,>Thread-1}
  MyRaceCondition.java:15         : p.update();
  MyRaceCondition.java:7          : x = x + y + x;
```

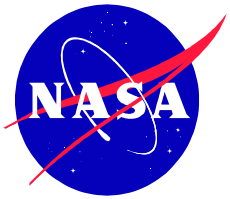
Detecting Deadlock



DEMO

MyRaceCondition2

Detecting Deadlock (1)

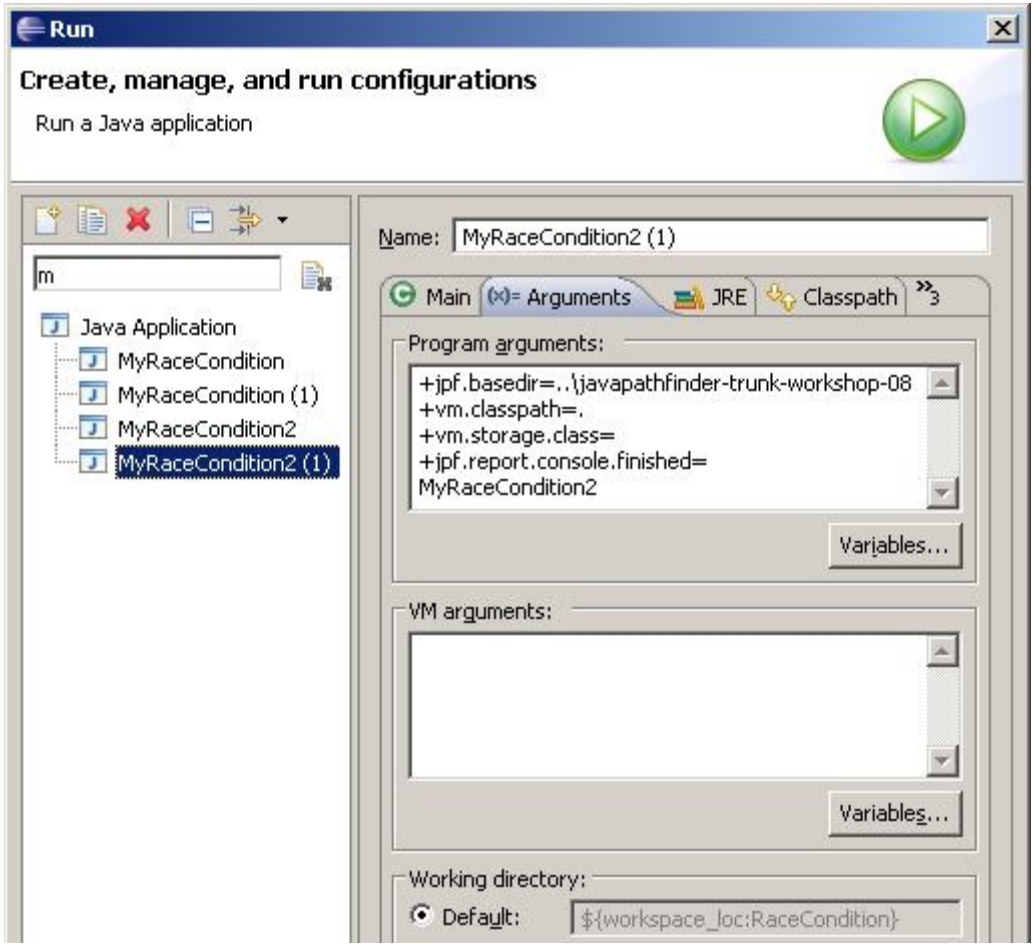



```
public class MyRaceCondition2 {
  private static class Pair {
    String x = "x";

    String y = "y";
    String z = "";

    public void update() {
      x = x + y + x;
    }}

  private static class RC1 extends Thread {
    Pair p;

    public void run() {
      synchronized (p.x) {
        synchronized (p.y) {
          p.update();
        }}}}

  private static class RC2 extends Thread {
    Pair p;

    public void run() {
      synchronized (p.y) {
        synchronized (p.x) {
          p.update();
        }}}}
```

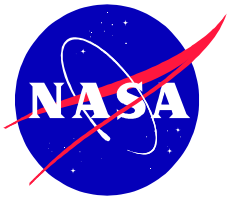
```
public static void main(String[] args) throws
Exception
{
  Pair p = new Pair();
  RC1 rc1 = new RC1();
  RC2 rc2 = new RC2();

  rc1.p = p;
  rc2.p = p;

  rc1.start();
  rc2.start();
  rc1.join();
  rc2.join();
  System.out.println("x: " + p.x);
  }}
```

Detecting Deadlock (2)

- Run changes:
  - no jpf.listener needed
  - test class: MyRaceCondition2



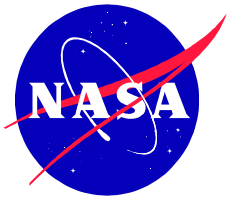
Detecting Deadlock (3)



Results:

```
========================================================= error #1
gov.nasa.jpf.jvm.NotDeadlockedProperty
deadlock encountered:
  thread index=0,name=main,status=WAITING,this=java.lang.Thread@0,target=null,priority=5,lockCount=1
  thread index=1,name=Thread-0,status=BLOCKED,this=MyRaceCondition2$RC1@226,priority=5,lockCount=0
  thread index=2,name=Thread-1,status=BLOCKED,this=MyRaceCondition2$RC2@247,priority=5,lockCount=0

... etc ...

========================================================= snapshot #1
thread index=0,name=main,status=WAITING,this=java.lang.Thread@0,target=null,priority=5,lockCount=1
  waiting on: MyRaceCondition2$RC1@226
  call stack:
     at java.lang.Thread.join(Thread.java:197)
     at MyRaceCondition2.main(MyRaceCondition2.java:47)

thread index=1,name=Thread-0,status=BLOCKED,this=MyRaceCondition2$RC1@226,priority=5,lockCount=0
  owned locks:java.lang.String@217
  blocked on: java.lang.String@219
  call stack:
     at MyRaceCondition2$RC1.run(MyRaceCondition2.java:18)

thread index=2,name=Thread-1,status=BLOCKED,this=MyRaceCondition2$RC2@247,priority=5,lockCount=0
  owned locks:java.lang.String@219
  blocked on: java.lang.String@217
  call stack:
     at MyRaceCondition2$RC2.run(MyRaceCondition2.java:30)

========================================================= search finished: 4/29/08 10:38 AM
```

Verify: Controlling JPF

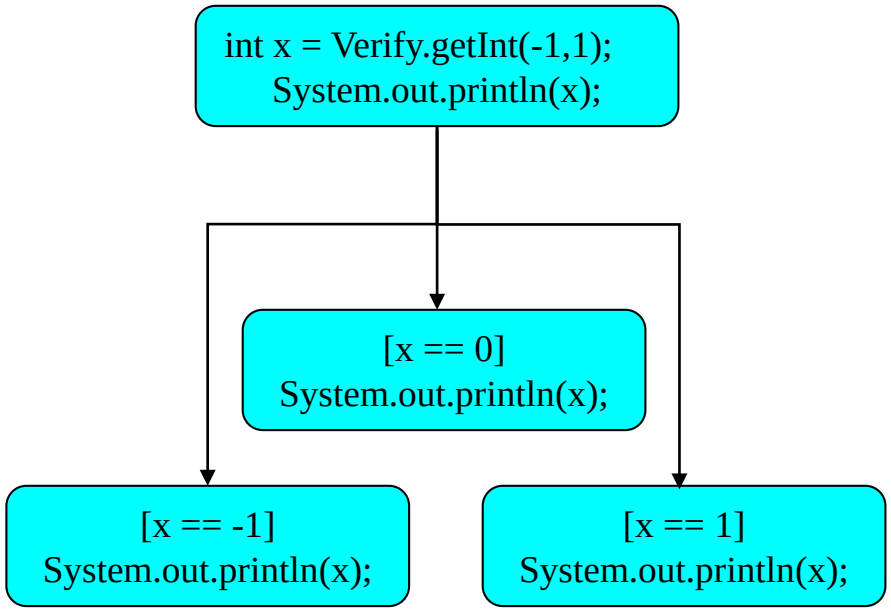


- The class `gov.nasa.jpf.jvm.Verify` lets you control simple aspects of JPF
  - Calls to `Verify` methods are specially recognized and handled by JPF
  - Search and backtracking
  - Counters
  - Logging
  - Attributes

Verify: Search (1)

- Choice Generators
  - When you need JPF to try alternatives:

    `Verify.getInt, getDouble, getBoolean,...`
  - When JPF hits `Verify.getXxx()`it branches the execution tree and executes one branch for each value



Verify: Search (2)

- Choice Generator Variations
  - Your code:

    ```
    double y = Verify.getDouble("Tag");
    ```

  - Your run config:

    ```
    +Tag.class=gov.nasa.jpf.jvm.choice.DoubleChoiceFromSet
    +Tag.values=-1.0:0.0:123.0
    ```

  - Result: your code runs with `y==-1.0`, `y==0.0`, and `y==123.0`
  - Other choice generators: see `gov.nasa.jpf.jvm.choice`

Verify: Search (3)

- **`Verify.ignoreIf()`:**

  Search Pruning

  - Forces JPF to abandon the current execution path and backtrack to the previous choice point
  - Useful when you know which parts of the execution search tree are irrelevant to you
  - Can speed up search dramatically (by ignoring parts of the search tree)

Verify: Search (4)

- Example: your method is not designed to handle cyclic graphs, but your test driver produces them

```
public void print(Graph g) {
  Verify.ignoreIf(g.isCyclic());
  ...
}
```

Verify: Search

DEMO

ShowVerify

ShowVerify2

Advanced Topic: Extending JPF

- JPF is extremely flexible: many ways to extend
  - Listeners and properties (example follows)
  - Model Java Interface (MJI): Library abstractions & adding code to the core
  - Redefining bytecodes (see Symbolic Execution and Numerics extensions on SourceForge)
  - Serializer/restorer (Saving and restoring states)
  - Publisher (Collecting and printing statistics and results in different formats)

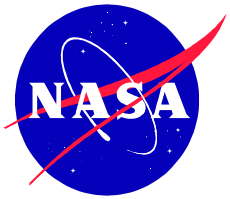
Advanced Topic: Listeners (1)

- Listeners are the preferred way of extending JPF
- You must know a bit about JPF internals to use them
- They give you access to JPF's internal execution

Advanced Topic: Listeners (2)

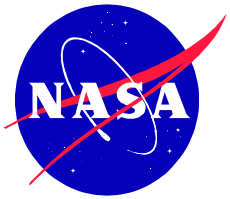
- Two flavors:
  `gov.nasa.jpf.search.SearchListener`
  `gov.nasa.jpf.jvm.VMListener`
- Interface `SearchListener:` observe search (backtracking, states' processing, property violation, ...)
- Interface `VMListener:` observe the VM's execution (bytecode execution, exceptions, thread starts, ...)

Advanced Topic: Listeners (3)



- Useful adapter class: `gov.nasa.jpf.ListenerAdapter` implements all the methods in `SearchListener` and `VMListener`.
- See JPF documentation (javapathfinder.sourceforge.net) and code for more details

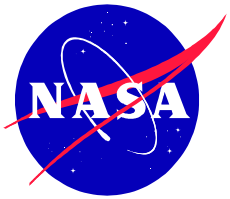
VMListener Example



DEMO

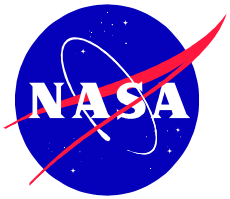
OpCodePrinter

VMListener Example




```
public class OpCodePrinter extends ListenerAdapter {
  String lastLoc = "";

  public void executeInstruction(JVM vm) {
    Instruction instr = vm.getNextInstruction();
    if (instr != null) {
      String loc = instr.getFileLocation();
      if (loc != null && ! loc.startsWith("java")) {
        if (! lastLoc.equals(loc)) {
          System.out.println(loc);
          lastLoc = loc;
        }
        System.out.println("   " + instr.getMnemonic().toUpperCase());
      }}}}
```

JPF Extensions

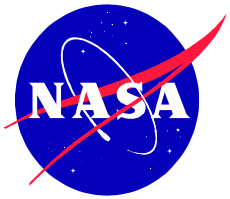


- Extensions found under `extensions/` in the JPF distribution
- Developed independently of JPF core
  - JPF core code should never refer to extension code
  - vice versa ok (of course!)
- Symbolic Execution (`extensions/symbc`)
- UML StateCharts (`extensions/statechart`)
- UI Model Checking (`extensions/ui`)
- Compositional Verification (`extensions/cv`)
- Numeric Properties (`extensions/numeric`)

Extension Example

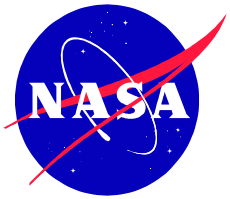
- Numerics Extension
  - Finds “bad” numerical behavior
    - integer and long overflow
    - floating point compares (NaN, infinity)
    - floating point inexact propagation (NaN, infinity)
    - floating point cancellation (lost precision)
  - How?
    - Write new bytecode implementations
    - Write bytecode factory

Numerics Extension



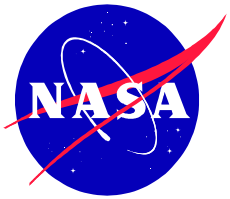
- Write InstructionFactory:
  - Tells JPF which bytecodes are being overridden and which classes to use for them
- Override numeric bytecodes:
  - Floating point comparisons: DCMPG, DCMPL, FCMPG, FCMPL
  - Floating point arithmetic: DADD, DSUB, DMUL, DDIV, FADD, FSUB, FMUL, FDIV
  - Int/long arithmetic: IADD, ISUB, IMUL, IDIV, IINC, LADD, LSUB, LMUL, LDIV
- Set config options

Numerics Extension (InstructionFactory)



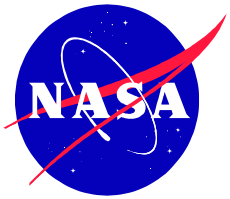

```
public class NumericInstructionFactory extends GenericInstructionFactory {

  // which bytecodes do we replace
  static final String[] BC_NAMES = {
    "DCMPG", "DCMPL",  "DADD", "DSUB", "DMUL", "DDIV",
    "FCMPG", "FCMPL",  "FADD", "FSUB", "FMUL", "FDIV",
    "IADD", "ISUB", "IMUL", "IDIV",  "IINC",
    "LADD", "LSUB", "LMUL", "LDIV"};

  // where do they reside
  protected static final String BC_PREFIX = "gov.nasa.jpf.numeric.bytecode.";

  // what classes should use them
  protected static final String[] DEFAULT_EXCLUDES = { "java.*", "javax.*" };


  public  NumericInstructionFactory (Config conf){
    super(BC_PREFIX, BC_NAMES, null, DEFAULT_EXCLUDES);
    NumericUtils.init(conf);
  }}
```

Numerics Extension (Original IMUL)



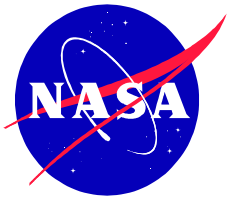

```
public class IMUL extends Instruction {
  public void setPeer (org.apache.bcel.generic.Instruction i,
                       ConstantPool cp) {
  }

  public Instruction execute (SystemState ss, KernelState ks,
                              ThreadInfo th) {
    int v1 = th.pop();
    int v2 = th.pop();

    th.push(v1 * v2, false);

    return getNext(th);
  }

  public int getByteCode () {
    return 0x68;
  }
}
```

Numerics Extension (Overridden IMUL)




```
public class IMUL extends gov.nasa.jpf.jvm.bytecode.IMUL {

  @Override
  public Instruction execute (SystemState ss, KernelState ks, ThreadInfo th) {
    int v1 = th.pop();
    int v2 = th.pop();

    // check for overflow
    if ((long)v1 * (long)v2 != v1 * v2){
      return th.createAndThrowException("java.lang.ArithmeticException",
                                        "integer overflow: " + v2 + "*" +
                                        v1 + "=" + v1*v2);
    }

    th.push(v1 * v2, false);

    return getNext(th);
  }
}
```

Numerics Extension



DEMO

NumericsExample

Numerics Extension (Config Options/Running)

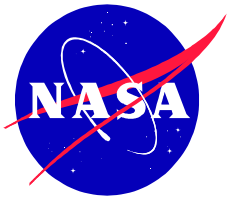
Recall:

- Main class: gov.nasa.jpf.JPF
- Classpath: include your JPF project

Config Program Arguments:

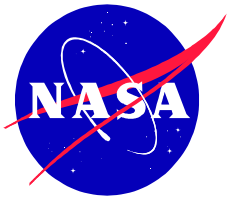
```
+jpf.basedir=..\javapathfinder-trunk-workshop-08
+vm.classpath=.
+vm.storage.class=
+jpf.report.console.finished=
+vm.insn_factory.class=gov.nasa.jpf.numeric.NumericInstructionFactory
NumericsExample
```

Numerics Extension (Output)




```
====================================================== error #1
gov.nasa.jpf.jvm.NoUncaughtExceptionsProperty
java.lang.ArithmeticException: integer overflow: 43046721*43046721=-501334399
              at NumericsExample.main(NumericsExample.java:6)


====================================================== trace #1

------------------------------------------------------ transition #0 thread: 0
gov.nasa.jpf.jvm.choice.ThreadChoiceFromSet {>main}
      [1864 insn w/o sources]
  NumericsExample.java:4          : int i = 3;
  NumericsExample.java:5          : for (int j=0; j<10; j++) {
  NumericsExample.java:6          : i = i * i;
          ... etc...
  NumericsExample.java:6          : i = i * i;
  NumericsExample.java:5          : for (int j=0; j<10; j++) {
  NumericsExample.java:6          : i = i * i;

====================================================== snapshot #1
```

References



- JPF: http://javapathfinder.sourceforge.net
- Eclipse: http://www.eclipse.org
- Subversion Plugin: http://subclipse.tigris.org
- Older but more advanced tutorial: http://www.visserhome.com/willem/presentations/ase06jpftut.ppt
- Survey of recent additions: http://dsrg.mff.cuni.cz/teaching/seminars/2007-06-26-Parizek-JPF4.pdf
- NASA Ames RSE group publications (including JPF): http://ti.arc.nasa.gov/tech/rse/publications/vandvpub.php#model
- Book on Model Checking theory (not JPF):

  Systems and Software Verification, by B. Berard, M. Bidoit, *et. al.*
- Model checking tutorials:

  Google for “model checking tutorial”