JavaPathFinder

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As a selection of slides from several JavaPathFinder tutorials
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Outline

* What is JPF
* Usage examples
* Test case generation
* JPF architecture
* Using JPF

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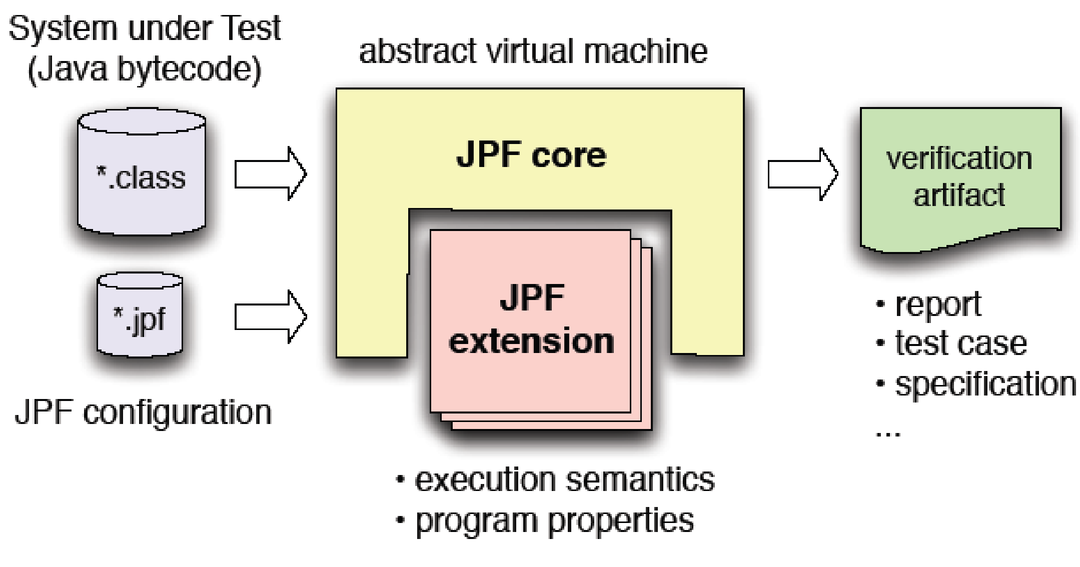
* **What is JPF**
* Usage examples
* Test case generation
* JPF architecture
* Using JPF

Introduction - What Is JPF?

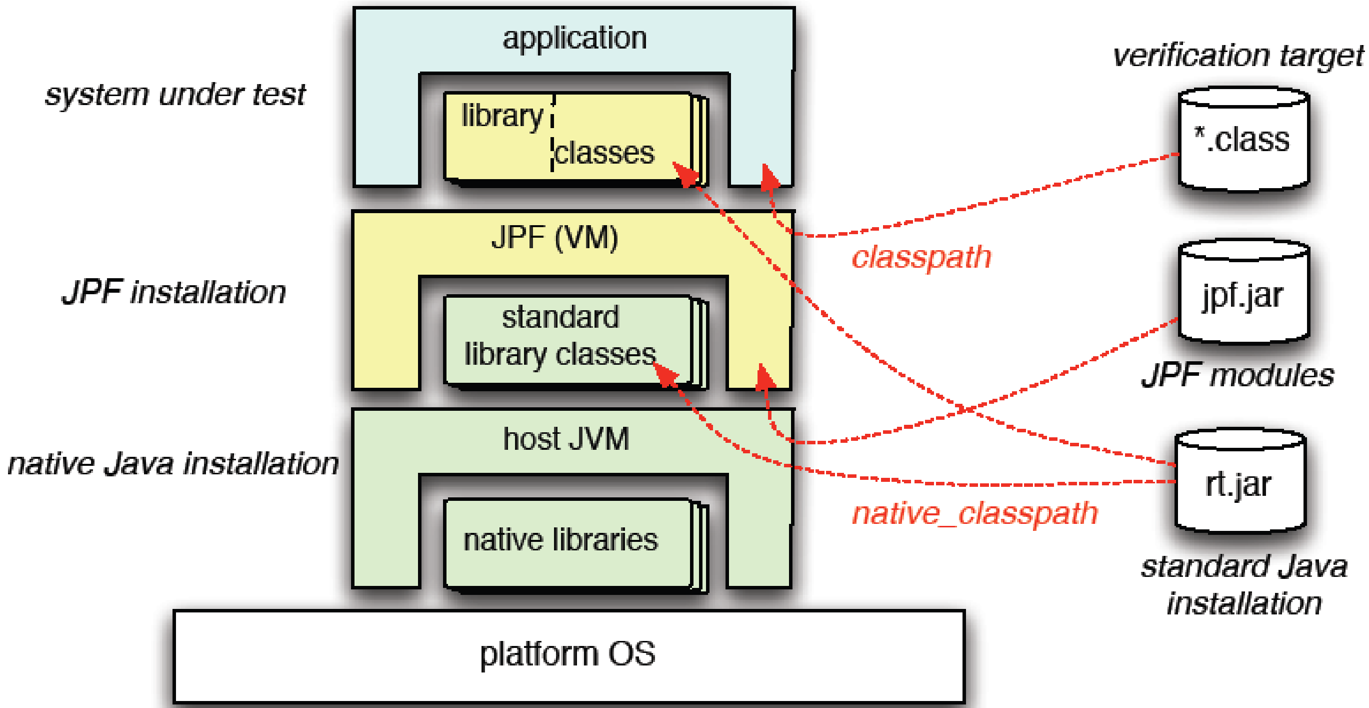
- surprisingly hard to summarize - can be used for many things
- extensible virtual machine framework for Java bytecode verification: workbench to efficiently implement all kinds of verification tools



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

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



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

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

JPF's Home

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

JPF's User Forum

http://groups.google.com/group/java-pathfinder

Where to learn more - the JPF-Wiki

Ames Research Center

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)

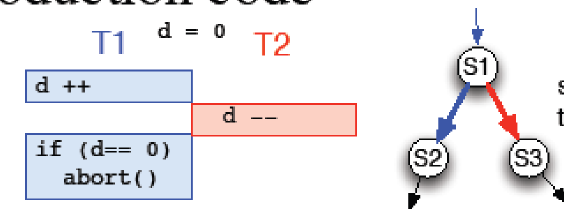
Outline

- What is JPF
- **Usage examples**
- Test case generation
- JPF architecture
- Using JPF

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)



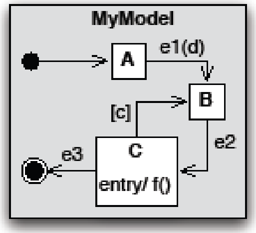
- deep inspection of production code
  - property annotations (Const, PbC,..)
  - numeric verification (overflow, cancellation)

```
@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

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JPF unaware programs

JPF enabled programs

JPF dependent programs

"sweet spot"

runs on any JVM

runs only under JPF

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

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

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

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

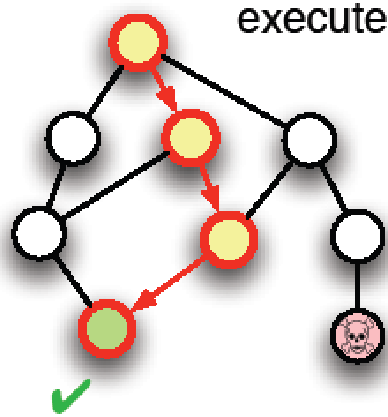
Model Checking vs. Testing

- 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:

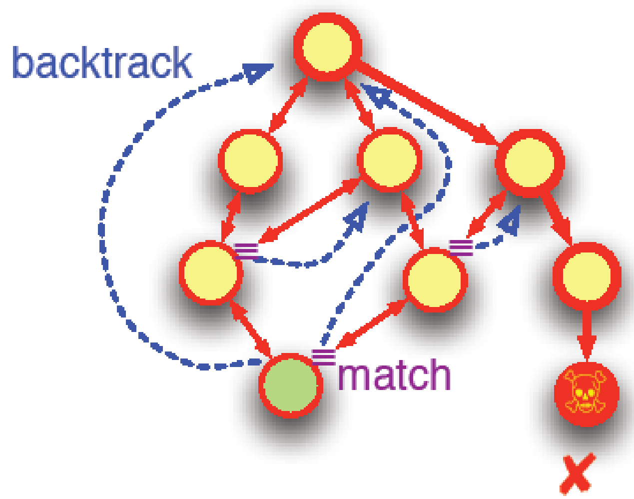
based on input set {d}
only one path
executed at a time

{d}

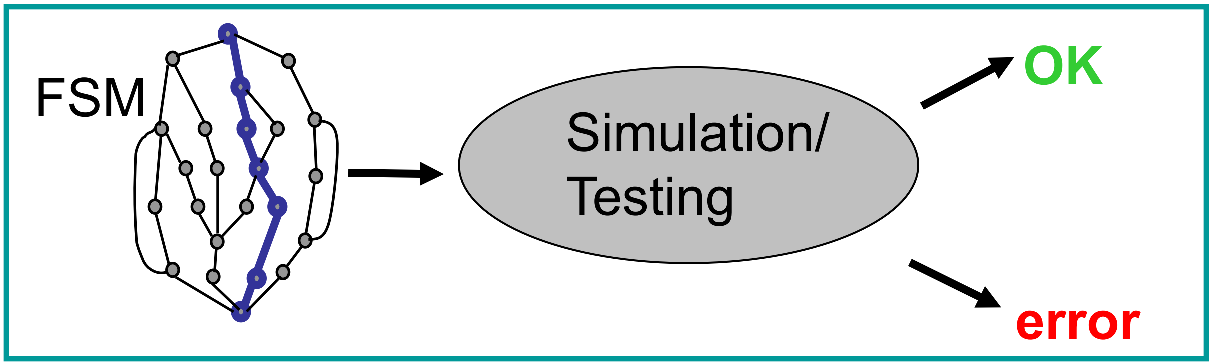


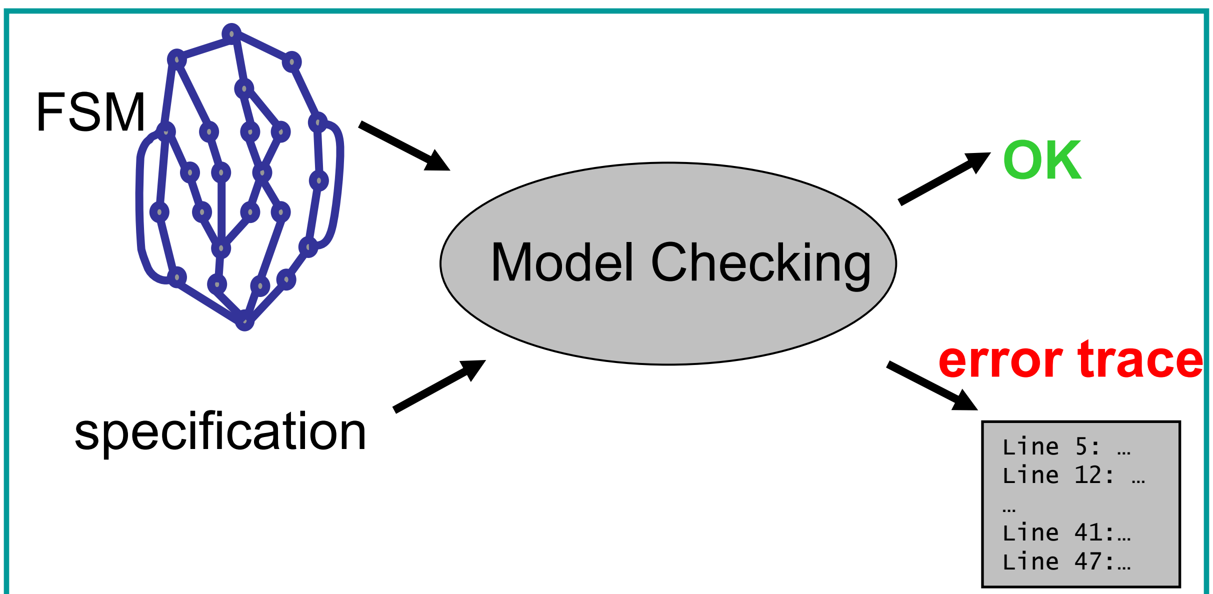
model checking:

all program state are explored
until none left or defect found



Model Checking vs. Testing/Simulation

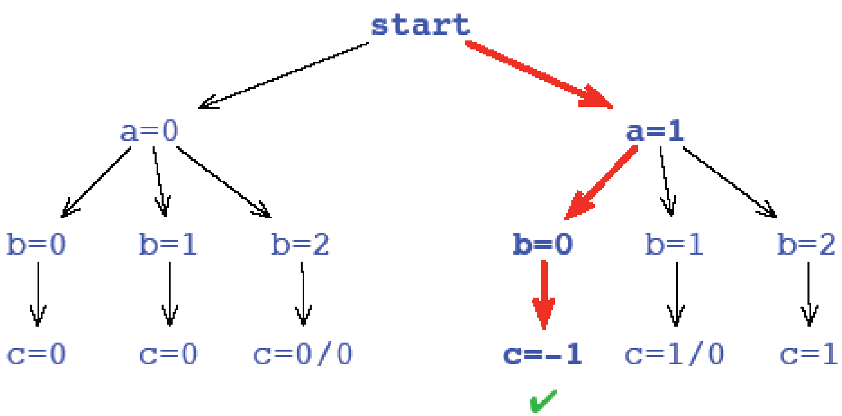




- Model individual state machines for subsystems / features
- Simulation/Testing:
  - Checks only some of the system executions
  - May miss errors
- Model Checking:
  - Automatically combines behavior of state machines
  - Exhaustively explores all executions in a systematic way
  - Handles millions of combinations – hard to perform by humans
  - Reports errors as traces and simulates them on system models

Example 1: Nondeterministic Data (2)

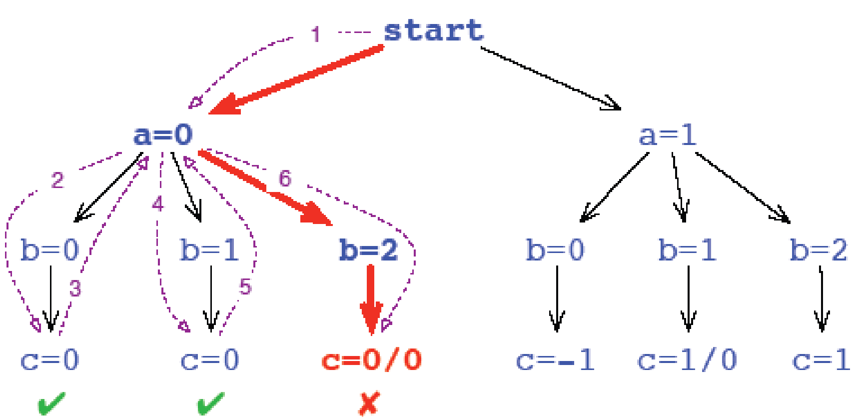
- Testing only covers one execution




```
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 8: Programming-by-Contract

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- 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

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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*

Symbolic Execution

- King [Comm. ACM 1976], Clarke [IEEE TSE 1976]
- Analysis of programs with unspecified inputs
  - Execute a program on symbolic inputs
- Symbolic states represent sets of concrete states
- For each path, build a path condition
  - Condition on inputs – for the execution to follow that path
  - Check path condition satisfiability – explore only feasible paths
- Symbolic state
  - Symbolic values/expressions for variables
  - Path condition
  - Program counter

Example – Standard Execution

Code that swaps 2 integers

```
int x, y;
if (x > y) {
  x = x + y;
  y = x – y;
  x = x – y;
  if (x > y)
    assert false;
}
```

Concrete Execution Path

x = 1, y = 0

↓

1 > 0 ? true

↓

x = 1 + 0 = 1

↓

y = 1 – 0 = 1

↓

x = 1 – 1 = 0

↓

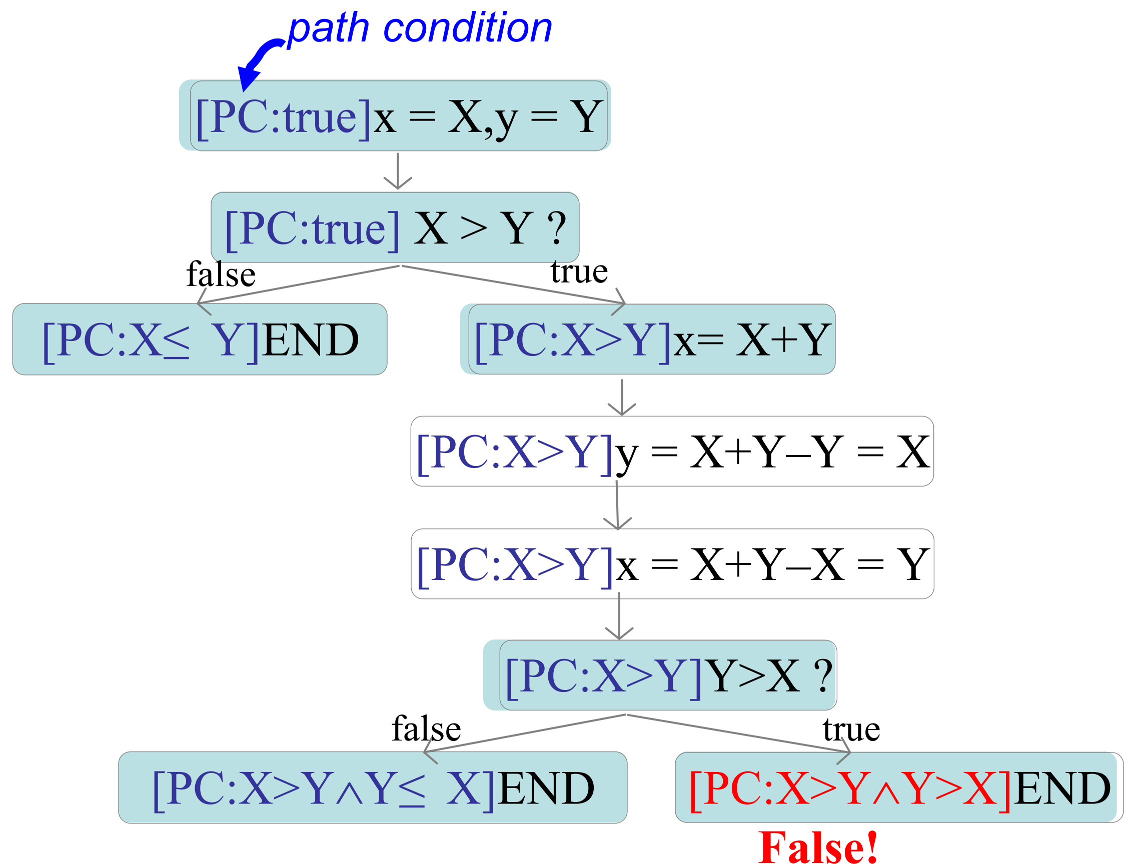
0 > 1 ? false

Example – Symbolic Execution

Code that swaps 2 integers:

```
int x, y;

if (x > y) {

  x = x + y;

  y = x – y;

  x = x – y;

  if (x > y)

    assert false;

}
```

Symbolic Execution Tree:



Solve path conditions → test inputs

Example 14: Symbolic Execution

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

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

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

```
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

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- 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

Symbolic PathFinder

- JPF-core's search engine used
  - To generate and explore the symbolic execution tree
  - To also analyze thread inter-leavings and other forms of non-determinism that might be present in the code
- No state matching performed – some abstract state matching
- The symbolic search space may be infinite due to loops, recursion
  - We put a limit on the search depth
- Off-the-shelf decision procedures/constraint solvers used to check path conditions
  - Search backtracks if path condition becomes infeasible
- Generic interface for multiple decision procedures
  - **Choco** (for linear/non-linear integer/real constraints, mixed constraints), http://sourceforge.net/projects/choco/
  - **IASolver** (for interval arithmetic) http://www.cs.brandeis.edu/~tim/Applets/IAsolver.html
  - **CVC3** http://www.cs.nyu.edu/acsys/cvc3/
  - Other constraint solvers: HAMPI, randomized solvers for complex Math constraints – work in progress

Implementation

- SPF implements a non-standard interpreter of byte-codes
  - To enable JPF-core to perform symbolic analysis
  - Replaces or extend standard concrete execution semantics of byte-codes with non-standard symbolic execution
- Symbolic information:
  - Stored in attributes associated with the program data
  - Propagated dynamically during symbolic execution
- Choice generators:
  - To handle non-deterministic choices in branching conditions during symbolic execution
- Listeners:
  - To print results of symbolic analysis (path conditions, test vectors or test sequences); to influence the search
- Native peers:
  - To model native libraries, e.g. capture `Math` library calls and send them to the constraint solver

Handling Branching Conditions

- Symbolic execution of branching conditions involves:
  - Creation of a non-deterministic choice in JPF's search
  - Path condition associated with each choice
  - Add condition (or its negation) to the corresponding path condition
  - Check satisfiability (with *Choco, IASolver, CVC3 etc.*)
  - If un-satisfiable, instruct JPF to backtrack
- Created new choice generator

```
public class PCChoiceGenerator
    extends IntIntervalGenerator {
    PathCondition[] PC;
    …
}
```

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Basics: a VM running inside JVM

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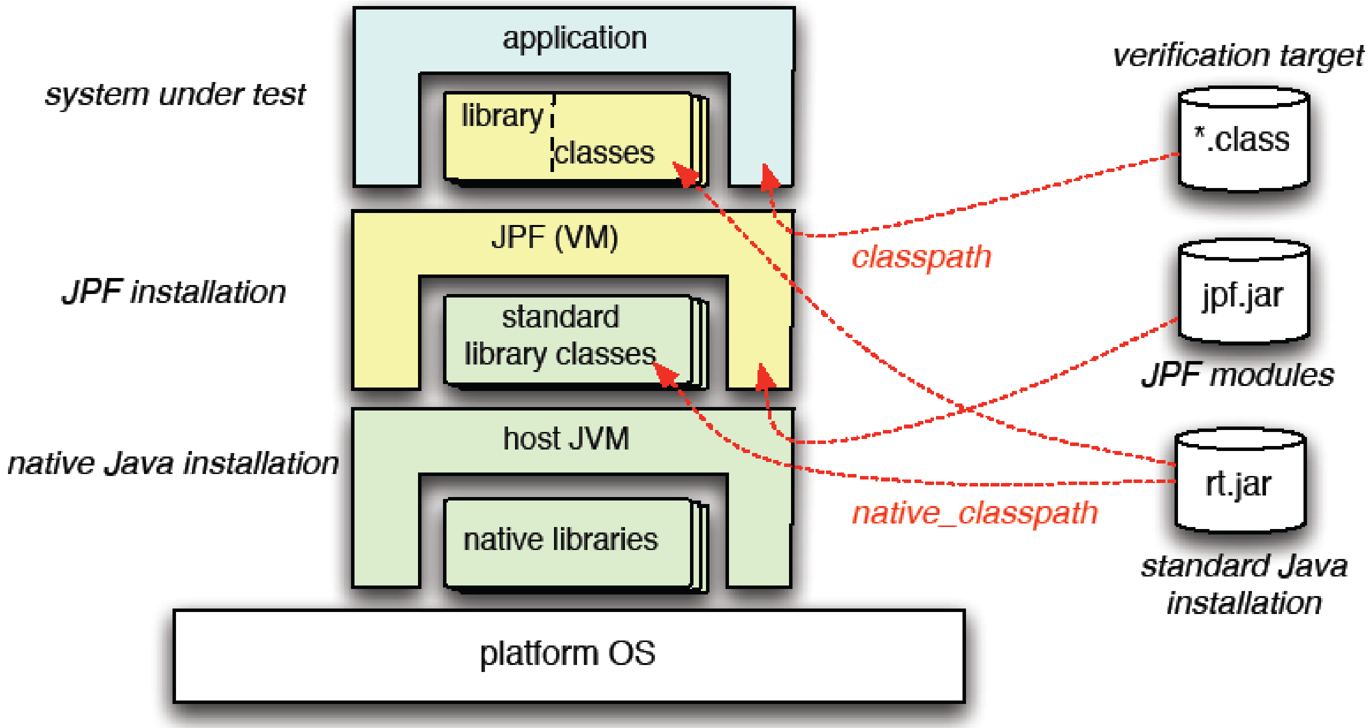
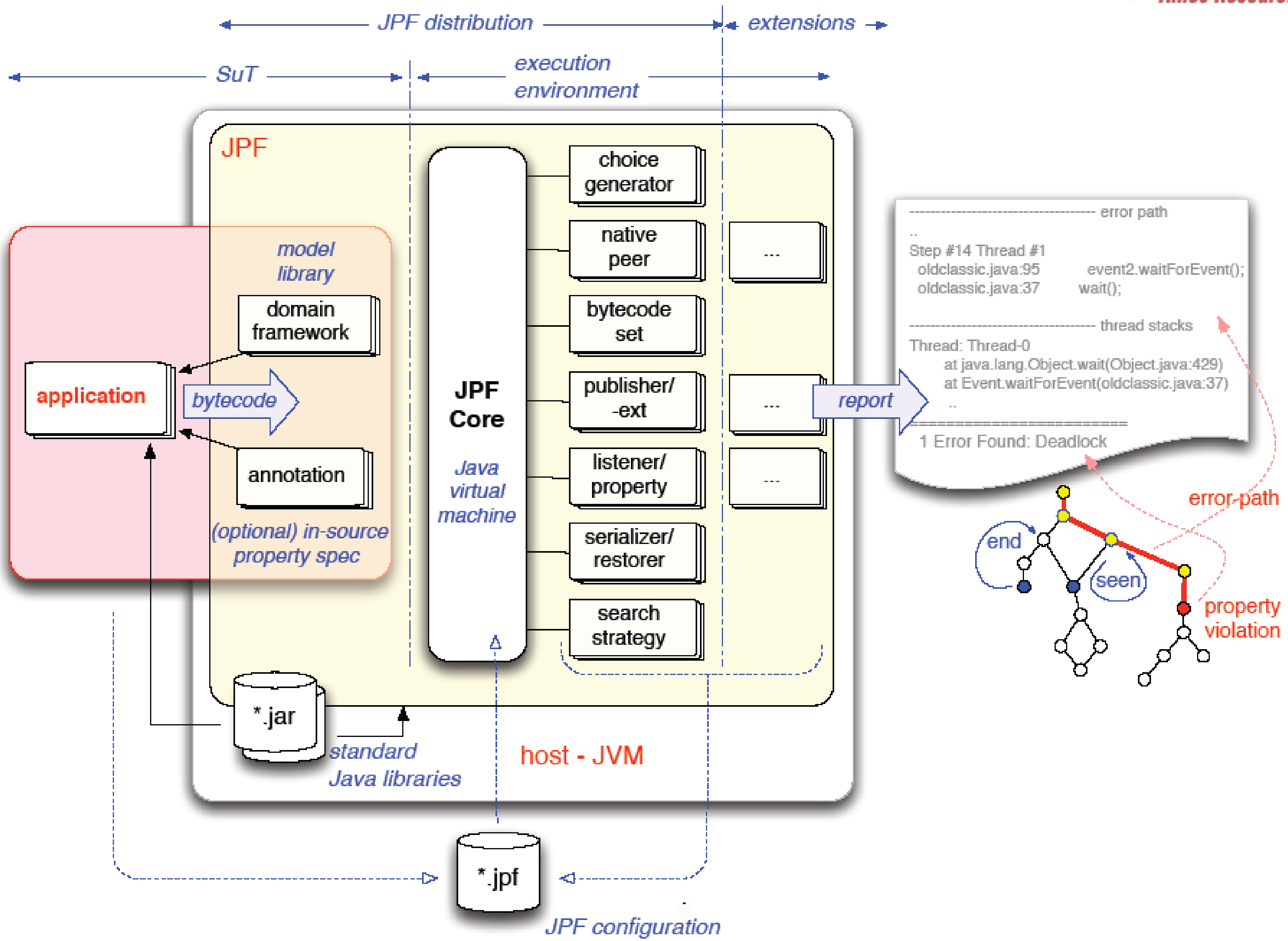
- verified Java program is executed by JPF, which is a virtual machine implemented in Java, i.e. runs on top of a host JVM
  $\Rightarrow$ easy to get confused about who executes what

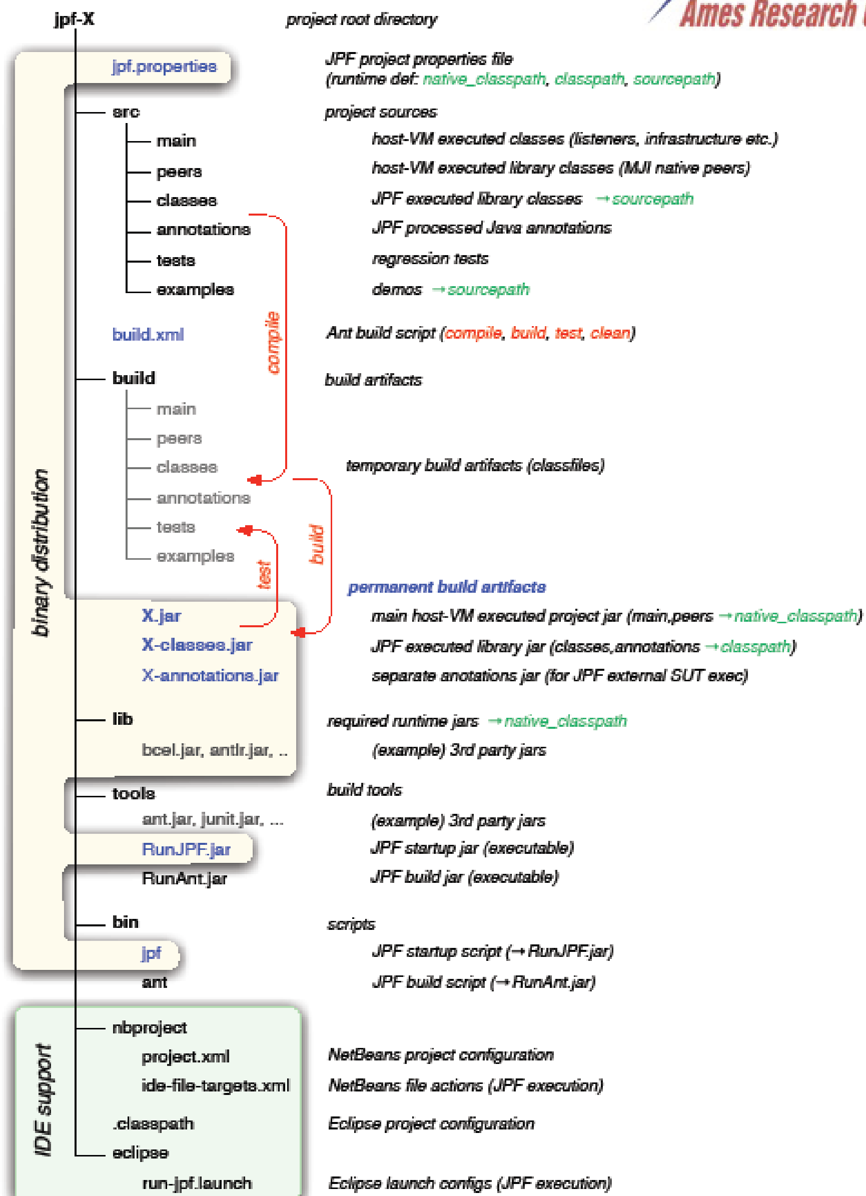


Basics: JPF Components



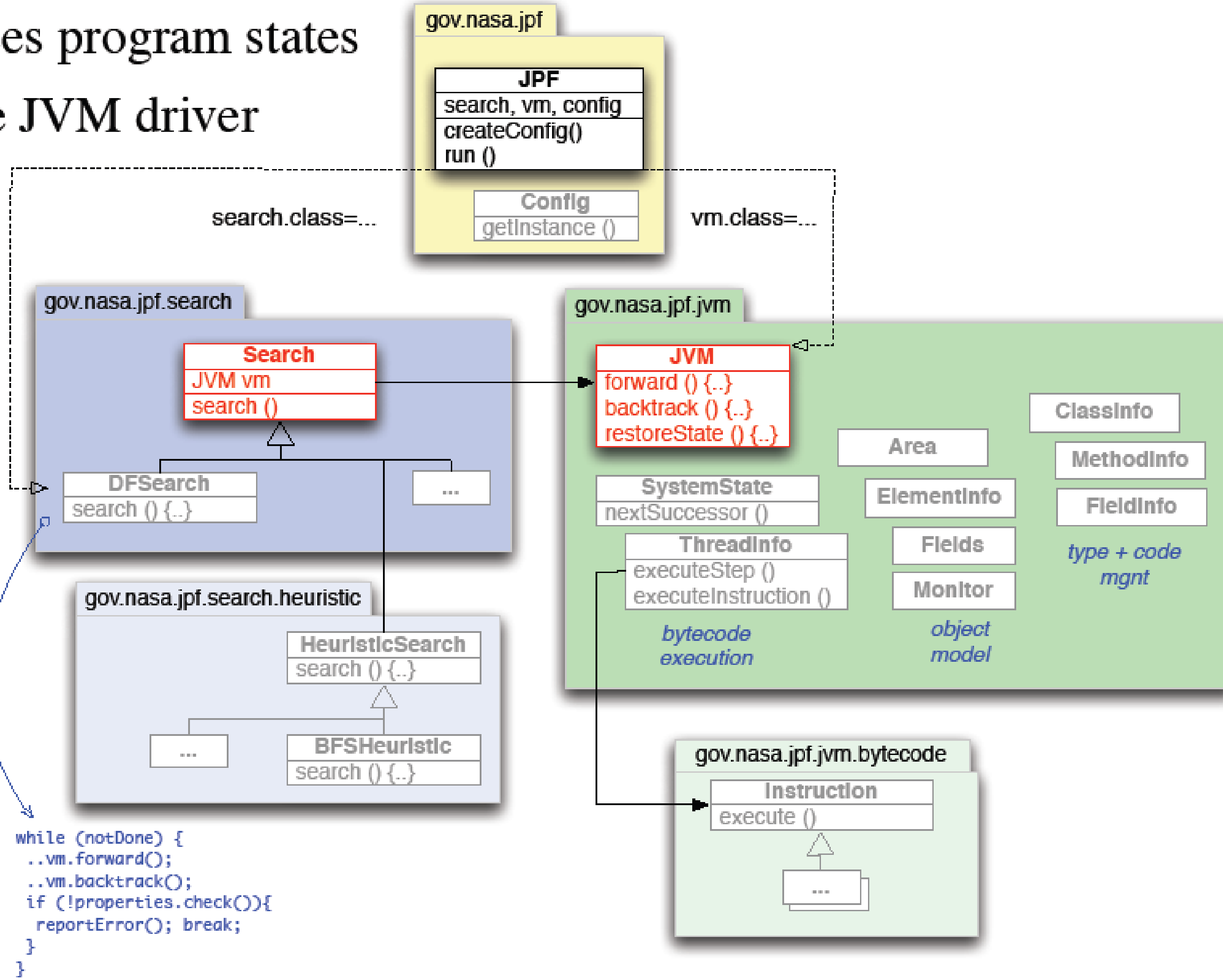
Basics: JPF Module/Project Structure

- all JPF projects share uniform directory layout
- binary distributions are slices of source distributions (interchangeable)
- 3rd party tools & libraries can be included (self-contained)
- all projects have examples and regression test suites (eventually ☹)
- projects have out-of-the-box IDE configuration (NB,Eclipse)



JPF Toplevel Structure

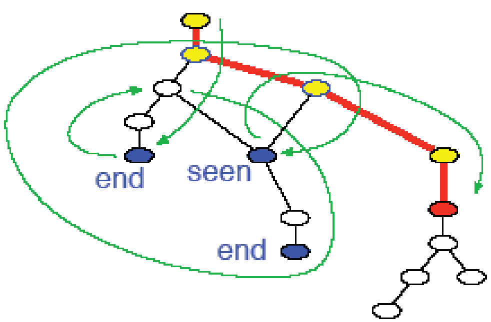
- two major constructs: Search and JVM
- JVM produces program states
- Search is the JVM driver



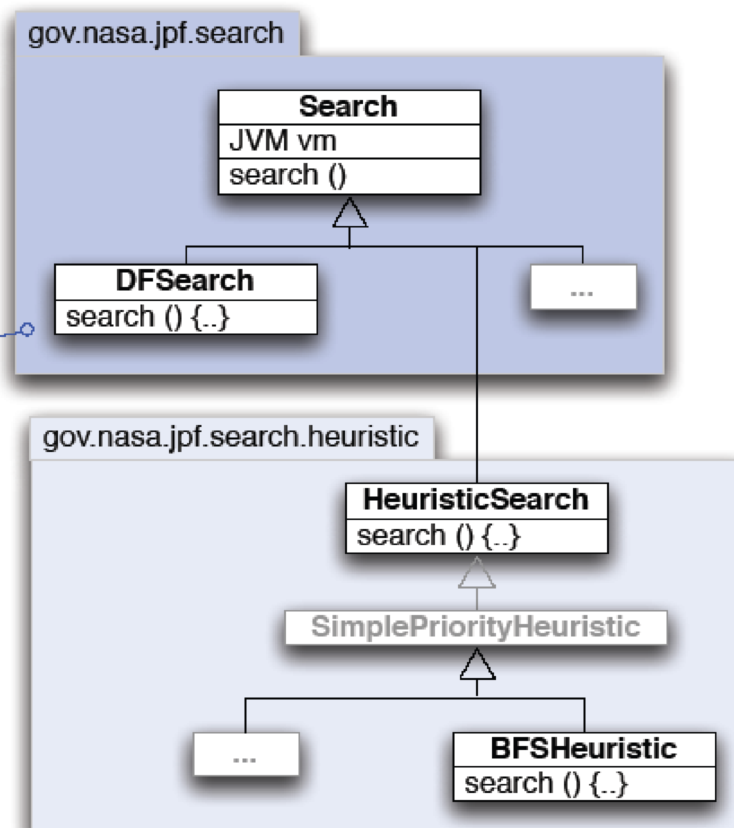
Search Policies

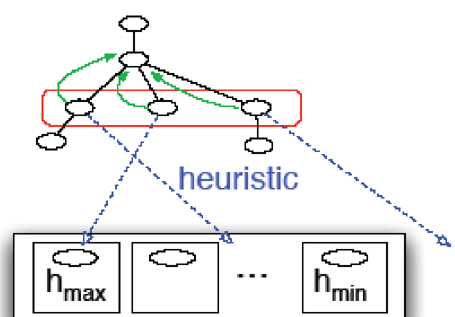
- state explosion mitigation: search the interesting state space part first ("get to the bug early, before running out of memory")
- Search instances encapsulate (configurable) search policies

```
while (notDone) {
 ..vm.forward();
 ..vm.backtrack();
 if (!properties.check()){
  reportError(); break;
 }
}
```



depth first traversal
optional state matching

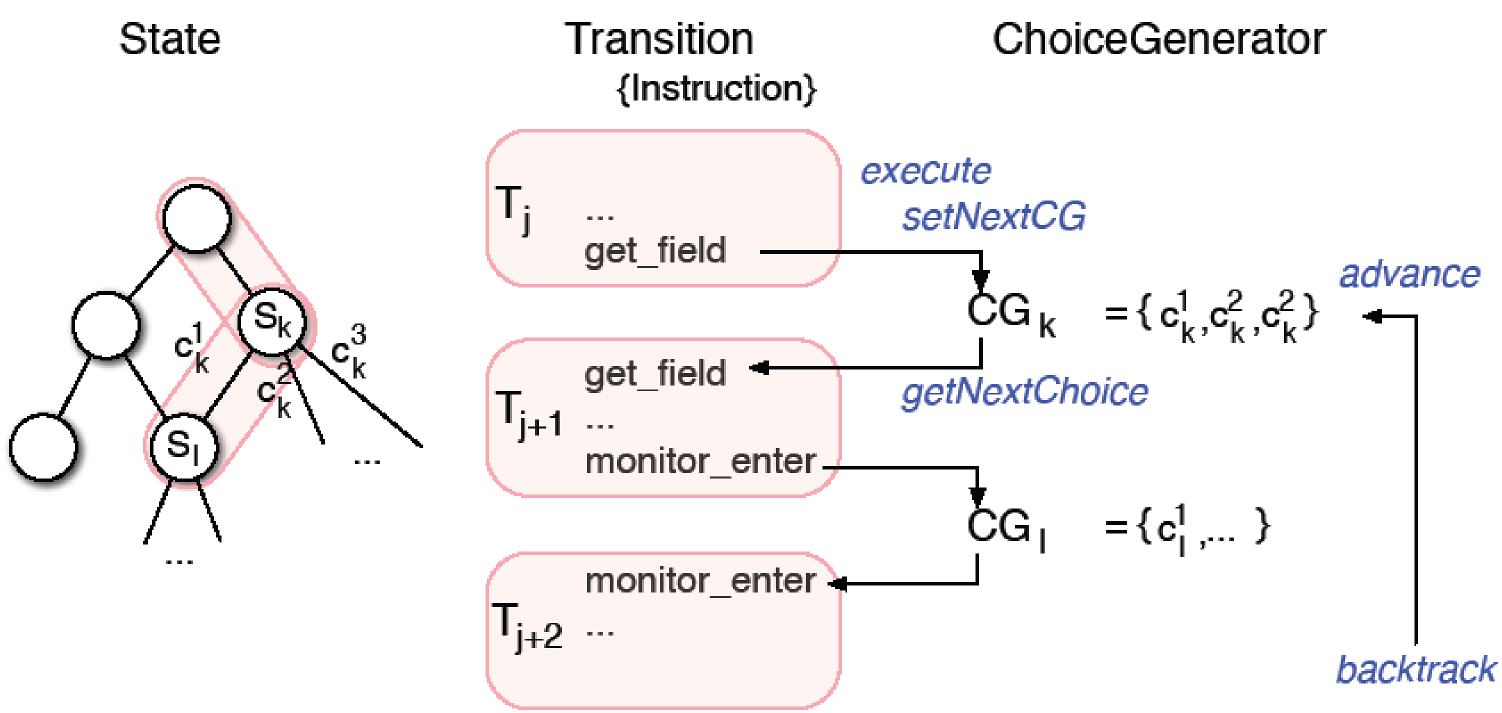




sorted state queue (bounded)

ChoiceGenerators - Transition Boundaries

- transitions begin with a choice and extend until the next ChoiceGenerator (CG) is set (by instruction, native peer or listener)
- 'advance' positions the CG on the next unprocessed choice (if any)
- 'backtrack' goes up to the next CG with unprocessed choices



Configurable ChoiceGenerators - Why?

`Verify.getBoolean()` C = { true, false } ✓

`Verify.getInt(0,4)` C = { 0, 1, 2, 3, 4 } ? potentially large sets with lots of uninteresting values

`Verify.getDouble(1.0,1.5)` C = { ∞ } ?? no finite value set without heuristics

xChoiceGenerator
choiceSet: {x}
hasMoreChoices() advance() getNextChoice() → x

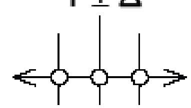
Choice Generators JPF internal object to store and enumerate a set of choices

+

Configurable Heuristic Choice Models configurable classes to create ChoiceGenerator instances

e.g. "Threshold" heuristic

T ± Δ



C = { T-Δ, T, T+ Δ }

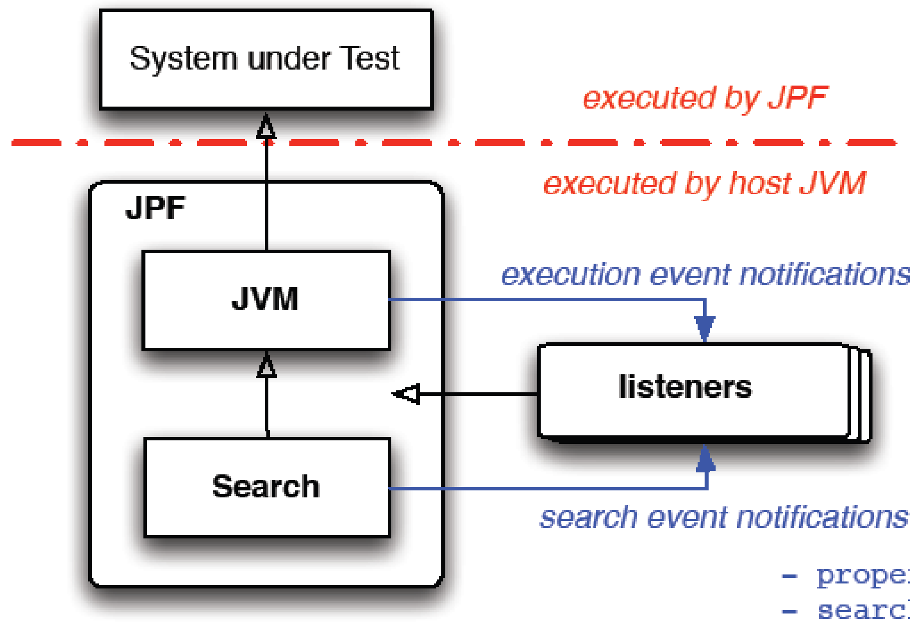
application code
(test driver)

```
..
double v = Verify.getDouble("velocity");
..
```

configuration
(e.g. mode property file)

```
velocity.class = gov.nasa.jpf.jvm.choice.DoubleThresholdGenerator
velocity.threshold = 13250
velocity.delta = 500
```

Listeners - the JPF plugins



- classLoaded()
- threadScheduled()
- threadNotified()
  ...
- executeInstruction()
- instructionExecuted()
- objectCreated()
  ...
- exceptionThrown()
  ...
- choiceGeneratorAdvanced()
  ...

configured

- +listener=<listener-class>
- @JPFConfig(..)
- listener.autoload=<annotations>
- jpf.addListener(..)
  ...

- propertyViolated()
- searchContraintHit
- searchFinished()
  ...

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Using JPF

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

Obtaining JPF

- Mercurial repositories on
  http://babelfish.arc.nasa.gov/hg/jpf/{jpf-core,jpf-aprop,...}
- Steps
  (1) obtain and install Mercurial (http://mercurial.selenic.com)
  (2) clone required JPF repositories

```
>hg clone http://babelfish.arc.nasa.gov/hg/jpf/jpf-core
>hg clone .../jpf/jpf-numeric
...
```

- don’t clone whole .../hg/jpf directory !
- don’t use https://.. (only required for push)
- alternative: download binary distributions from wiki project page attachments (e.g. http://babelfish.arc.nasa.gov/trac/jpf/wiki/projects/jpf-core) - not recommended at this time

Installing, Building and Testing JPF

- create `site.properties` file in `${user.home}/jpf` directory
  (see http://babelfish.arc.nasa.gov/trac/jpf/wiki/install/site-properties, required so that JPF can find jpf-core and installed projects without extensive manual classpath configuration)

```
jpf-core = ${user.home}/projects/jpf/jpf-core
...
jpf-numeric = ${user.home}/projects/jpf/jpf-numeric
extensions+=,${jpf-numeric}
...
```

- build & test jpf-core and required extensions
  (with included Ant builder)

```
>cd jpf-core
>bin/ant clean test
...
>cd ../jpf-numeric
>bin/ant clean test
...
```

```
$ bin/ant clean test
Buildfile: .../jpf-core/build.xml
clean:
   [delete] Deleting directory .../jpf-core/build
-init:
    [mkdir] Created dir: .../jpf-core/build
...
build:
      [jar] Building jar: .../jpf-core/build/jpf.jar
test:
    [junit] Running TypeNameTest
    [junit] Tests run: 1, Failures: 0, Errors: 0...
    ...
BUILD SUCCESSFUL
Total time: 1 minute 30 seconds
```

JPF Configuration (1)

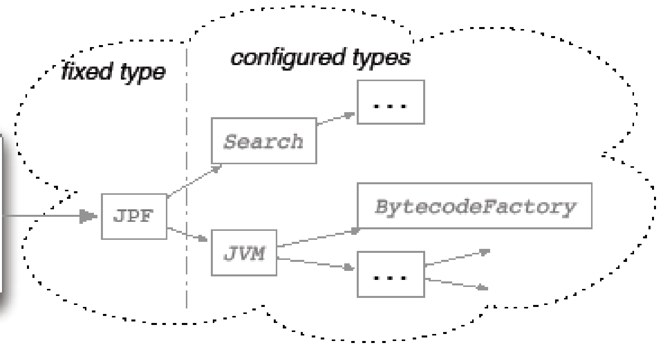
- almost nothing in JPF is hardwired ⇒ great flexibility but config can be intimidating
- all of JPFs configuration is done through Java properties (but with some extended property file format)
  - keyword expansion `jpf-root = ${user.home}/jpf`
    - previously defined properties
    - system properties
  - append `extensions+=,jpf-aprop`
  - prepend `+peer_packages=jpf-symbc/build/peers,`

    no space between key and '+' !
  - directives
    - dependencies `@requires jpf-awt`
    - recursive loading `@include ../jpf-symbc/jpf.properties`
- hierarchical process
  - system defaults (from jpf.jar)
  - site.properties
  - project properties from all site configured projects (<project-dir>/jpf.properties)
  - current project properties (./jpf.properties)
  - selected application properties file (*.jpf)
  - command line args (e.g. `bin/jpf +listener=.listeners.ExecTracker ...`)

JPF Configuration (2)

Config object

```
..
myheuristic.some_value=42
search.class=..BFSHeuristic
vm.class=..JVM
..
```



=

java -jar ...RunJPF.jar {+*key*=*value*..} [-show] [-log] *<application>.jpf*

debug
`-show` prints used property values
`-log` prints used file sources

command line properties

```
> java -jar ..RunJPF.jar
      +myheuristic.some_value=42   MyTestApp.jpf
```

\+

application properties

```
target = MyTestApp
target_args = ..
search.class = \
  gov.nasa.jpf.search.heuristic.BFSHeuristic
```

.../myproject/myapplication.jpf
specifies the main class of the system under test

\+

project properties

```
jpf-awt.native_classpath = build/jpf-awt.jar..
jpf-awt.classpath = build/jpf-awt-classes.jar..
jpf-awt.sourcepath = src/classes..
...
```

.../jpf/<component>/jpf.properties
specifies paths to run the JPF component

\+

site properties

```
jpf-core = ${user.home}/projects/jpf/jpf-core

jpf-awt = ${user.home}/projects/jpf/jpf-awt
extensions+=,${jpf-awt}
...
```

~/.jpf/site.properties
specifies which JPF components are installed

\+

default properties

```
..
vm.class = gov.nasa.jpf.jvm.JVM
search.class = gov.nasa.jpf.search.DFSearch
..
```

.../jpf.jar!/gov/nasa/jpf/default.properties
provides required default values

Running JPF

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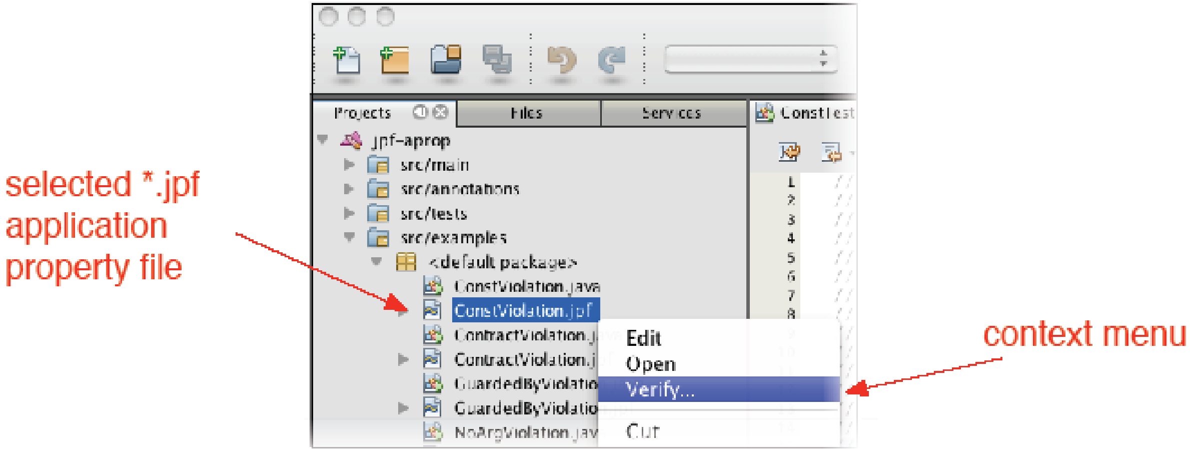
- for purists (tedious, do only if you have to)
  - setting up classpaths `>export CLASSPATH=...jpf-core/build/jpf.jar...`
  - invoking JVM `>java gov.nasa.jpf.JPF +listener=... x.y.MySUT`
- using site config and starter jars (much easier and portable)
  - explicitly `>java -jar tools/RunJPF.jar MySUT-verify.jpf`
  - using scripts `>bin/jpf MySUT-verify.jpf`
- running JPF from within JUnit
- running JPF from your program (tools using JPF)
- using NetBeans or Eclipse plugins
  - "Verify.." context menu item for selected *.jpf application property file
  - using provided launch configs (Eclipse) or run targets (NetBeans)

Running JPF from NetBeans

- use project provided run/debug tasks (requires nbproject/ide-file-targets.xml in project)
  - select *.jpf file in projects view
  - invoke Run→Run File from menubar (not in context menu)
  - results in Output view
- use NetBeans JPF plugin from http://babelfish.arc.nasa.gov/trac/jpf/wiki/projects/netbeans-jpf
  - download & install attached *.nbm if you don't want to build
  - optionally install jpf-shell extension if you want JPF to run in own window
  - launch JPF by selecting *.jpf file and invoking "Verify.." context menu item



Running JPF from Eclipse

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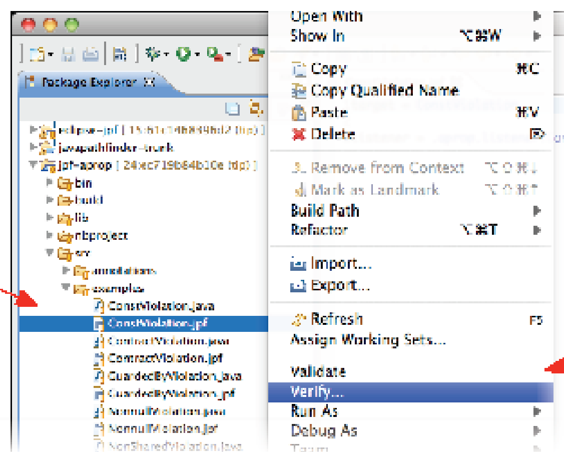
- use project provided launch configuration (requires eclipse/run-JPF.launch in project)
  - select *.jpf file in projects view
  - invoke Run As→Run Configurations→run-JPF from context menu
  - results in Output view
- use Eclipse JPF plugin from http://babelfish.arc.nasa.gov/trac/jpf/wiki/projects/eclipse-jpf
  - install from update site if you don’t want to rebuild http://babelfish.arc.nasa.gov/trac/jpf/raw-attachment/wiki/install/eclipse-plugin/update/
  - optionally install jpf-shell extension if you want JPF to run in own window
  - launch JPF by selecting *.jpf file and invoking “Verify..” context menu item

selected *.jpf application property file



context menu

Using JPF Shell

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- sometimes JPF reports too long for IDE Output view
- some applications / properties might require specific visualization
- solution: configured JPF shell
- specify shell class and views in your application property file (*.jpf)
- launch normally through "Verify" context menu
- JPF shell shows as separate window
- sources can be shown in IDE editors by clicking links in JPF shell window

```
# JPF application property file using generic JPF shell
target=oldclassic
...
shell=.shell.basicshell.BasicShell
shell.panels+=,searchgraph
...
```

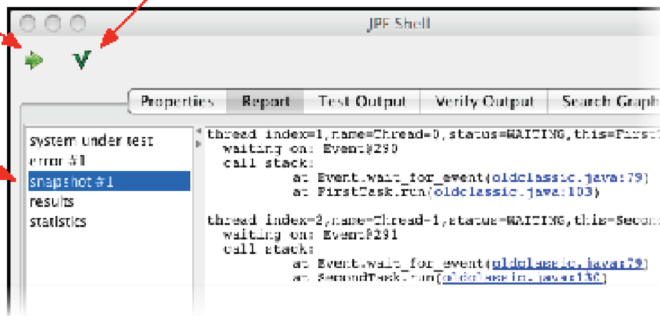
Why Using JPF Shell ?

run SUT (test)

run JPF (verify)

browse complex reports

browse report topics

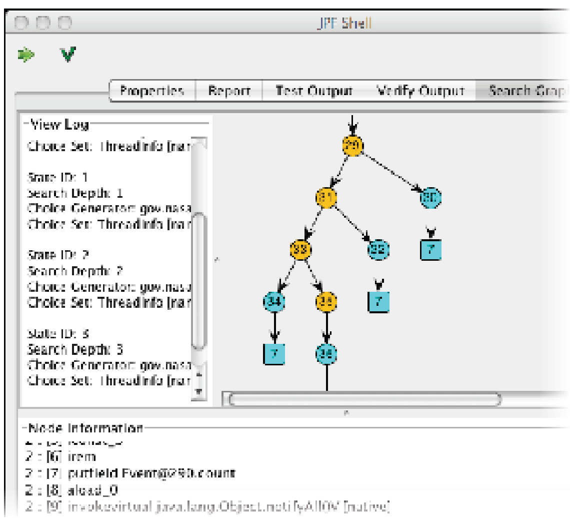


configurable view tabs

```
shell=.shell.basicshell.BasicShell
shell.panels=...
```

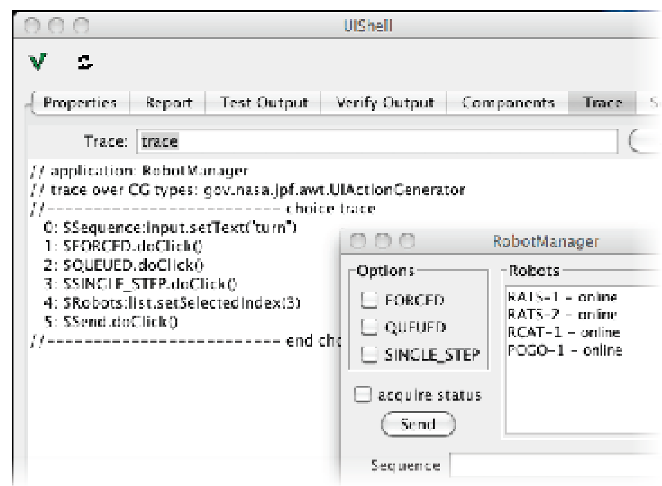
clickable source links

inspect JPF run




```
.. shell.panels+=,searchgraph
```

application/domain specific views




```
shell=.shell.awt.UIShell
shell.panels+=,component,trace,script
```