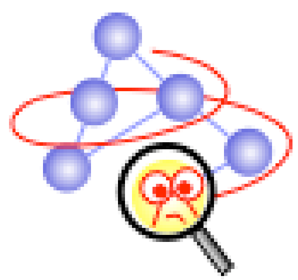
Model Checking Programs with Java PathFinder ~ Part 2: Design



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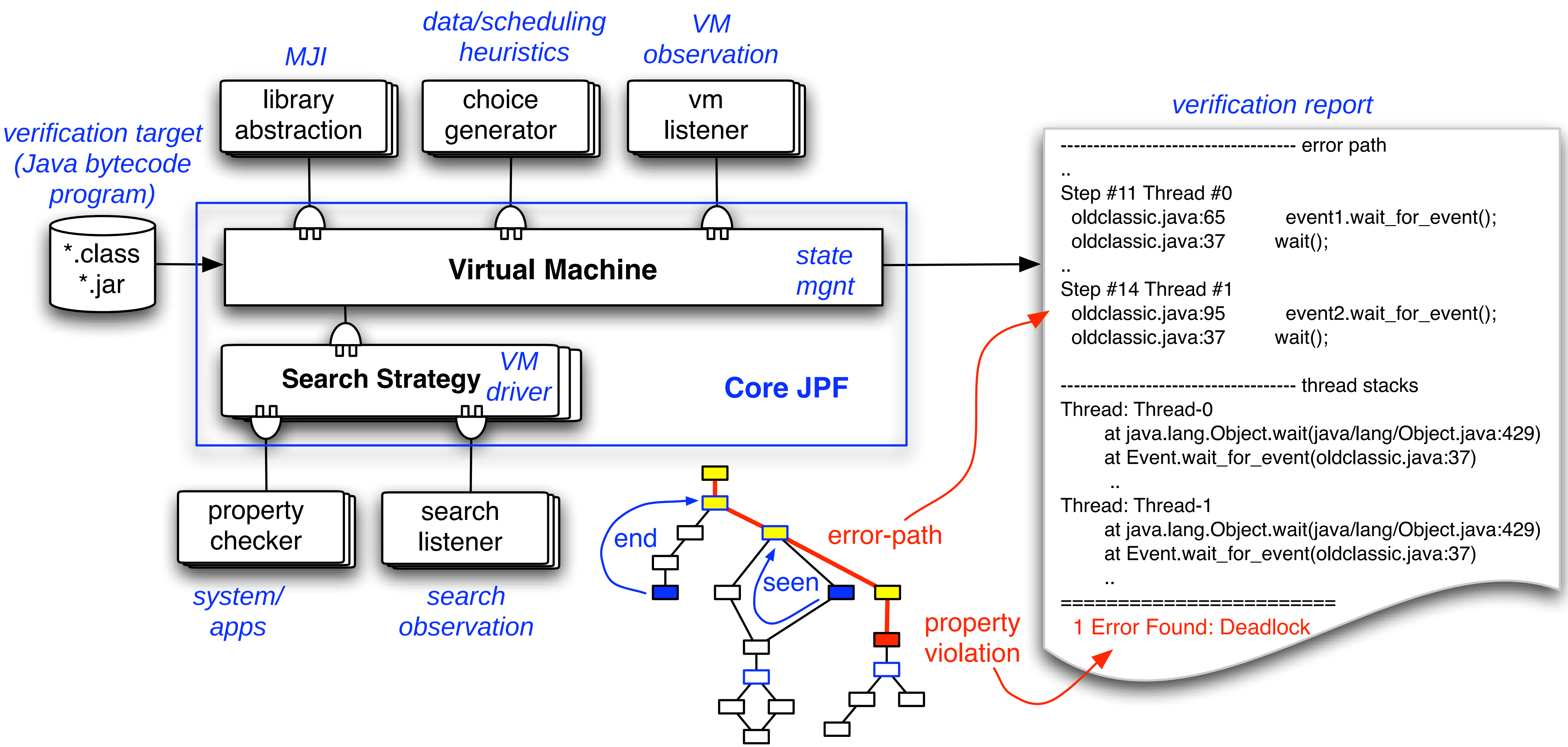
Roadmap

- What is JPF?
- Motivating Examples
- How To Run It
  - invocation, configuration, distribution components
- Basic JPF Design
  - Search, VM
- Extending JPF
  - Listeners
  - Properties
  - MJI
- Underlying Mechanisms
  - Partial Order Reduction
- Future Infrastructure
  - ChoiceGenerator (yet another extension mechanism)

What is Java PathFinder (1)

- explicit state model checker for Java bytecode
- focus is on finding bugs in Java programs
  - concurrency related: deadlocks, (races), missed signals etc.
  - Java runtime related: unhandled exceptions, heap usage, (cycle budgets)
  - but also: complex application specific assertions



What is JPF (2)

- goal is to avoid modeling effort (check the real program), or at least use a real programming language for complex models
- implies that the main challenge is scalability
- JPF uses a variety of scalability enhancing mechanisms
  - user extensible state abstraction & matching
  - on-the-fly partial order reduction
  - configurable search strategies: "find the bug before you run out of memory"
  - user definable heuristics (searches, choice generators)
- key issue is configurable extensibility: overcome scalability constraints with suitable customization (using heuristics)

JPF Status

- developed at the Robust Software Engineering Group at NASA Ames Research Center
- currently in it's fourth development cycle
  - v1: Spin/Promela translator - 1999
  - v2: backtrackable, state matching JVM - 2000
  - v3: extension infrastructure (listeners, MJI) - 2004
  - v4: symbolic execution, choice generators - 4Q 2005
- open sourced since 04/2005 under NOSA 1.3 license: <javapathfinder.sourceforge.net>
- it's a first: no NASA system development hosted on public site before
- 7500 downloads since publication 04/2005

Motivating Examples

- not your usual model checking examples
- oldclassic : concurrency (missed signal causing a deadlock)
- Crossing (AKA “stoned hippies”) : JPF extension mechanisms
- K9 Rover : ‘real’ model, size (partial order reduction)

How To Run JPF

- generally speaking: like a VM (“java” replacement):

```
> bin/jpf <jpf-options> <test-app main class>
```

- BUT: lots of configuration (classes) and parameterization (booleans, integers etc.)
- JPF is an open system
- need for flexible, extensible configuration system
- quite powerful, but can be somewhat confusing

JPF Configuration

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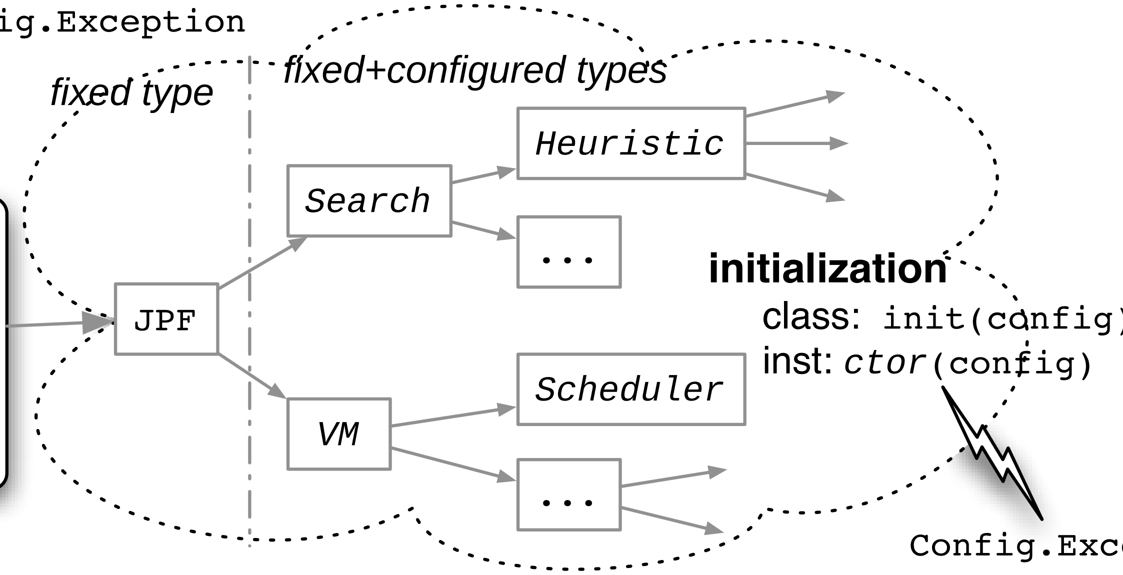
```
class gov.nasa.jpf.Config {
  Object getInstance(key,type) throws Config.Exception
  Object getEssentialInstance(key,type)..
  boolean getBoolean(key) ..
}
```



Config.Exception
- missing entry
- wrong type
- general exception

Config object

```
..
myheuristic.some_value=42
search.class=..HeuristicSearch
search.heuristic.class=MyHeuristic
vm.class=..JVM
..
```

(=)

java {-vm-arg..} gov.nasa.jpf.JPF [-c *config-file*] {+*key*=*value*..} [-show] *main-class* {*app-arg*..}

command line properties

```
> java gov.nasa.jpf.JPF  -c bfs.properties
    +search.heuristic.class=MyHeuristic
    +myheuristic.some_value=42
      MyTestApp
```

(+)

mode properties

```
# breadth first JPF configuration
search.class = \
  gov.nasa.jpf.search.heuristic.HeuristicSearch
search.heuristic.class = \
  gov.nasa.jpf.search.heuristic.BFSHeuristic
```

location

- command-line specified file
- or `jpf.properties` in JPF root dir
- or `jpf.properties` resource in jar
  (loaded via `gov.nasa.jpf.JPF`)

(+)

default properties

```
# section 1: general properties
log = warning
..
# section 2: Search properties
search.class = gov.nasa.jpf.search.DFSearch
..
# section 3: JVM properties
vm.class = gov.nasa.jpf.jvm.JVM
..
```

- `default.properties` in JPF root dir
- or `default.properties` resource in jar
  (loaded via `gov.nasa.jpf.JPF`)

Directory Structure

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```
jpf3/
  src/ .............. root dir for all JPF sources (build.xml,jpf.properties..)
    gov/nasa/jpf/ .. common types, abstraction interfaces (JPF,Search,VM..)
      jvm .......... core VM classes (JVM..)
      search/ ...... search classes (AbstractSearch,DFSearch..)
        heuristic .. heuristics classes
      tools ........ various JPF  listeners (ExecTracker,HeapTracker..)
      uti .......... auxiliary classes

  env/ .............. MJI standard library sources
    jpf ............ model classes (java.lang.Class..)
    jvm ............ native peer classes (JPF_java_lang_Class..)

  test/ ............ JPF regression test suite
    jvm ............ core VM tests
    mc ............. model checking tests

  doc .............. documentation (JPF.pdf)

  extensions/ ...... root dir for optional JPF extensions
    LTL2Buchi ...... extension example (same dir structure like JPF)
      src/* ........ extension source root
      doc/ ......... optional  extension documentation
      lib/ ......... optional extension libraries (required for build&run)
      bin/ ......... optional run scripts etc.
    ...
--------------------------------------------------------------------
  build-tools/ ..... JPF  build environment
    bin ............ applications and scripts (ant..)
    lib ............ build-tool libraries (junit.jar,ant.jar..)

  build/ ........... JPF classfiles (binaries)
    jpf ............ core JPF
    env ............ standard libraries
    test ........... regression tests

  lib .............. libraries required to run JPF (bcel.jar,fast-md5.zip..)

  bin .............. scripts to run JPF (jpf..)
```

src

env

test

doc

extensions

build

lib

bin

optional

sources

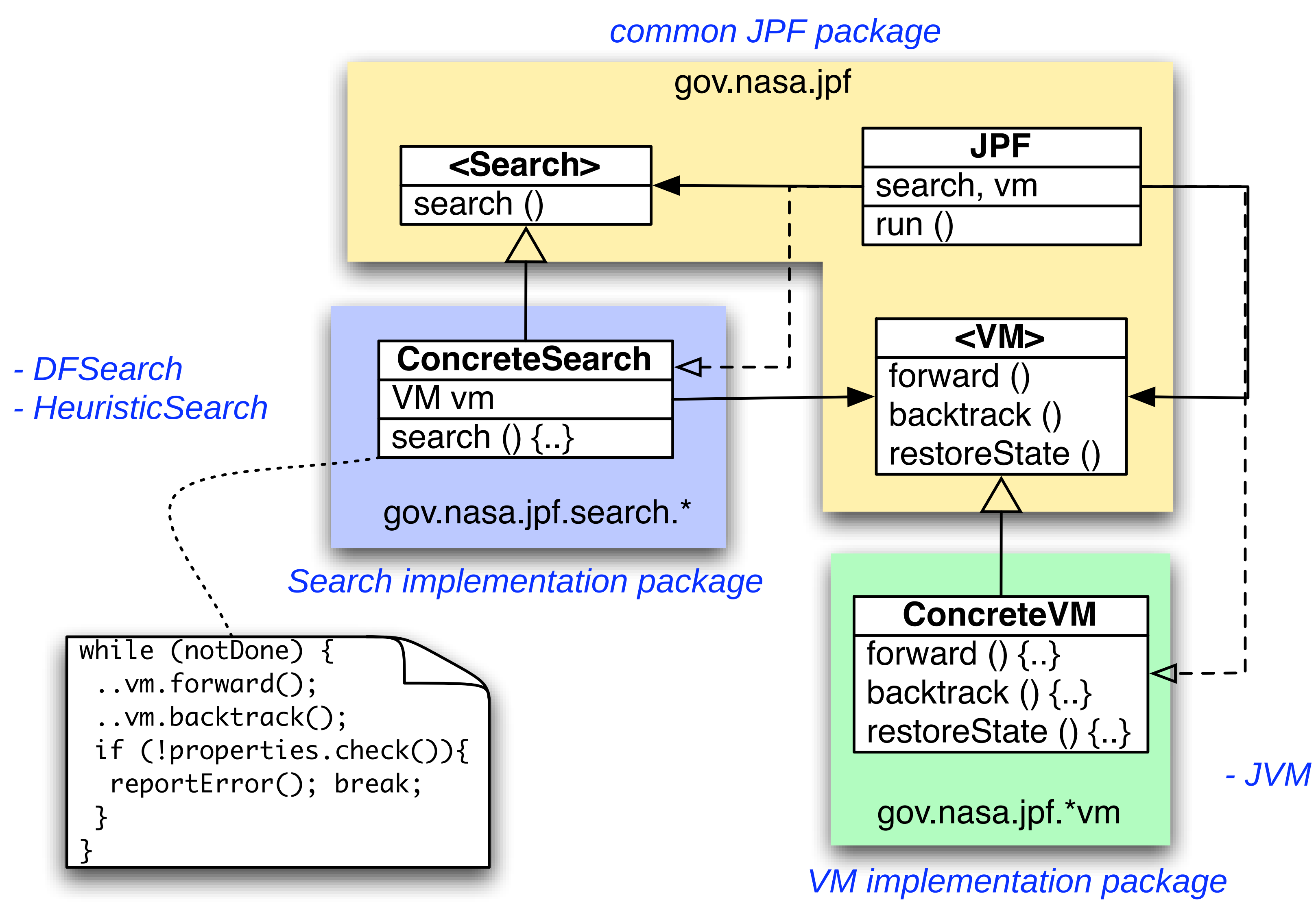
optional

binaries

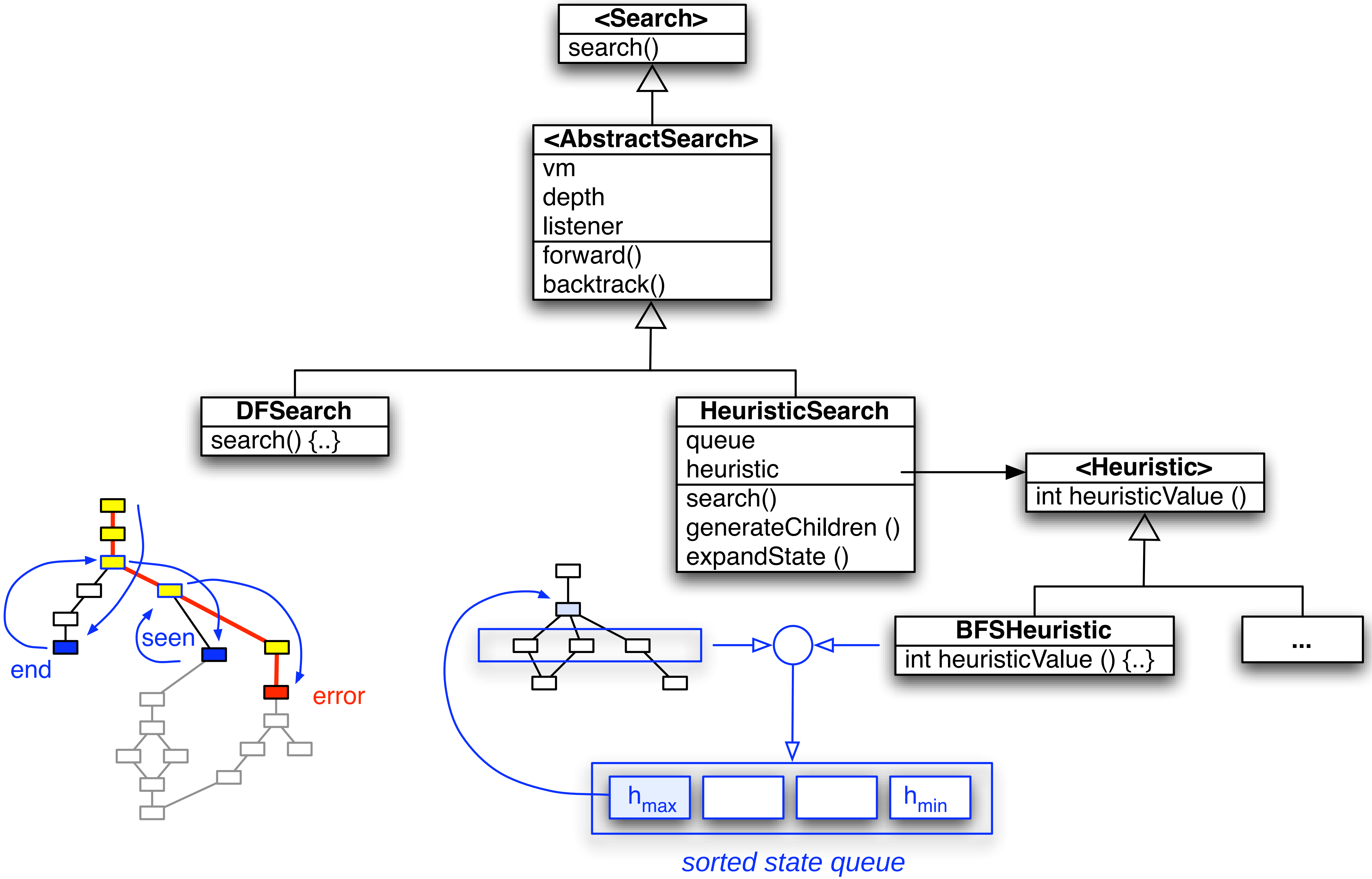
dynamic

Under the Hood - Toplevel Structure

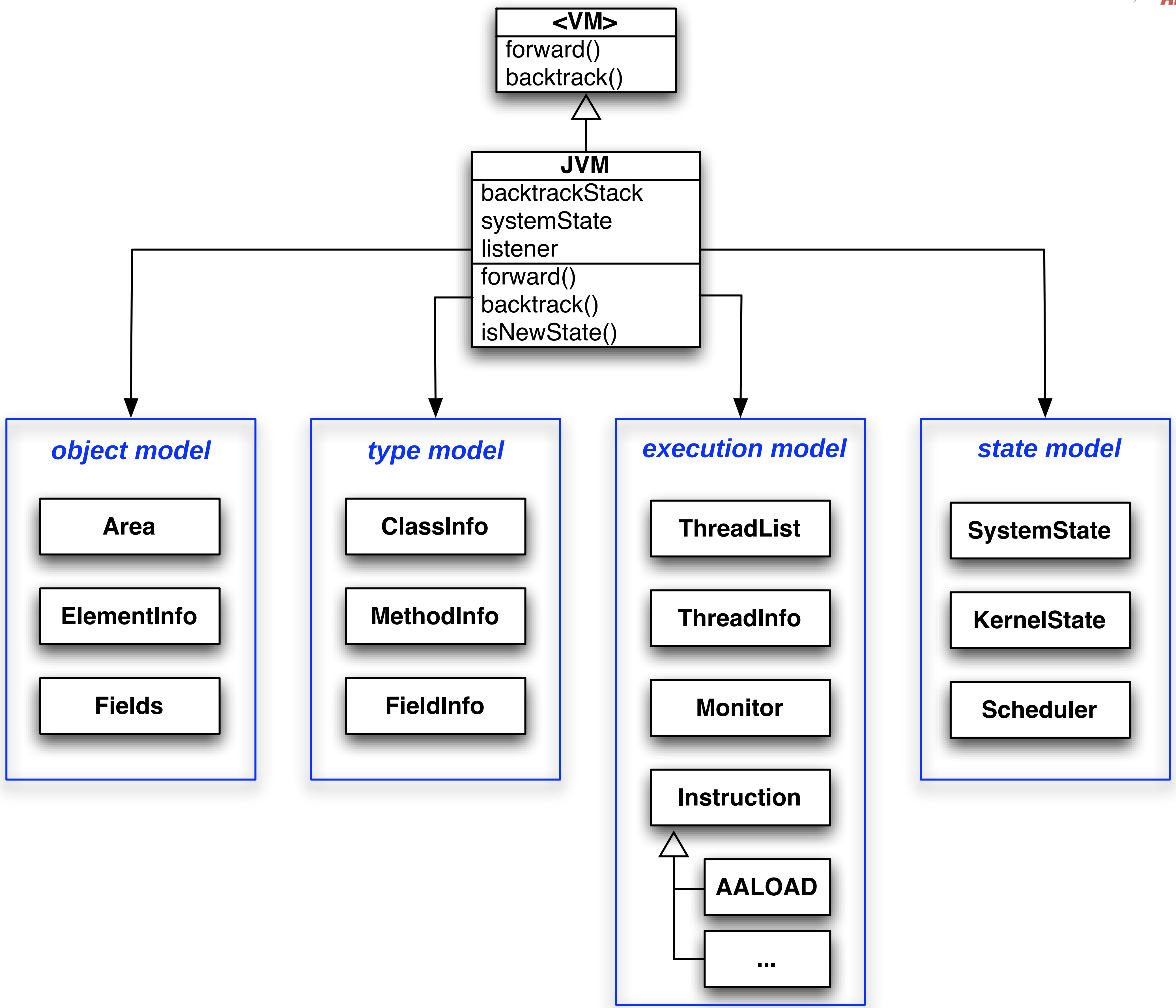
- two major concepts: Search and VM
- Search is the VM driver and Property evaluator
- VM is the state generator



Under the Hood - Search

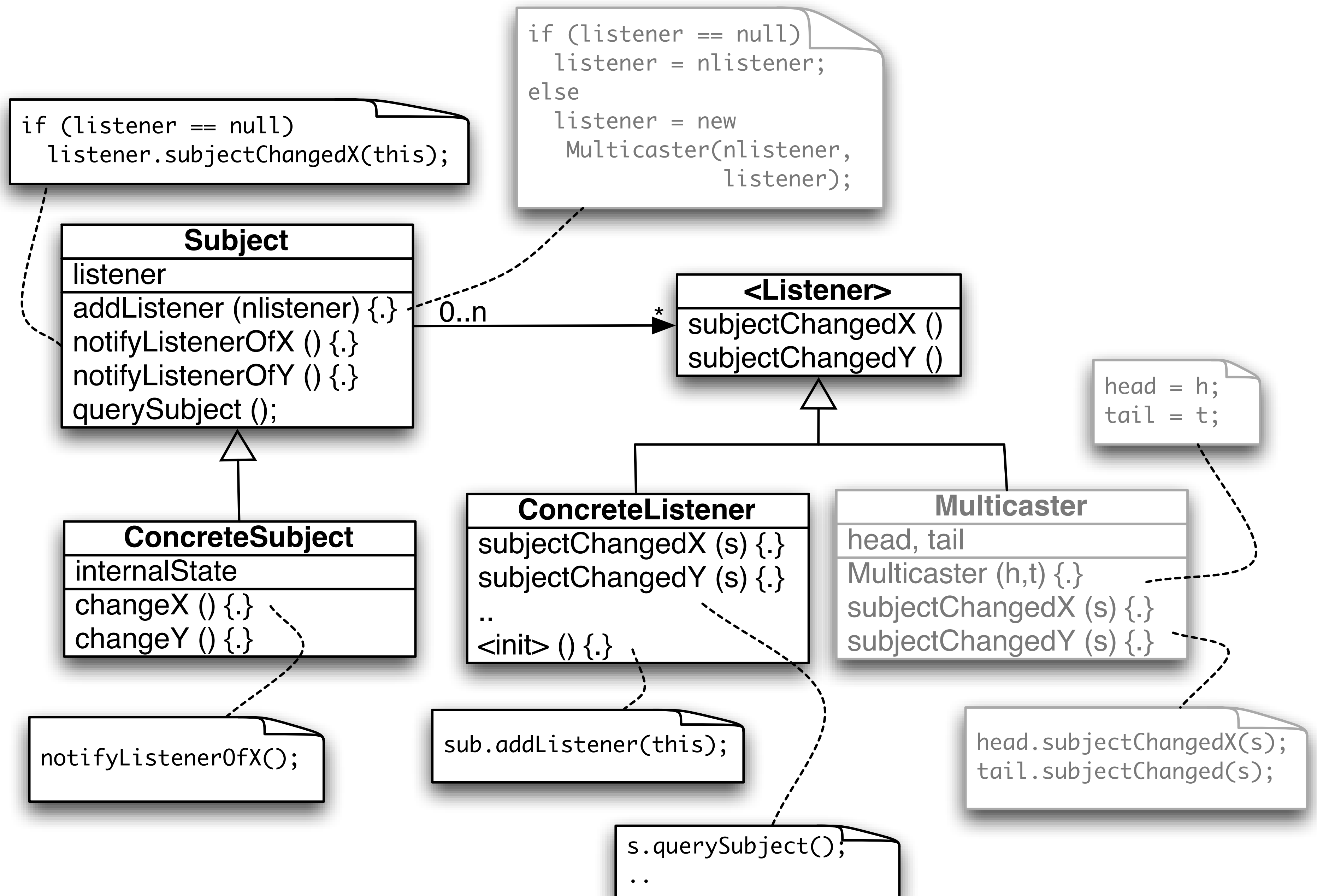


Under the Hood - VM



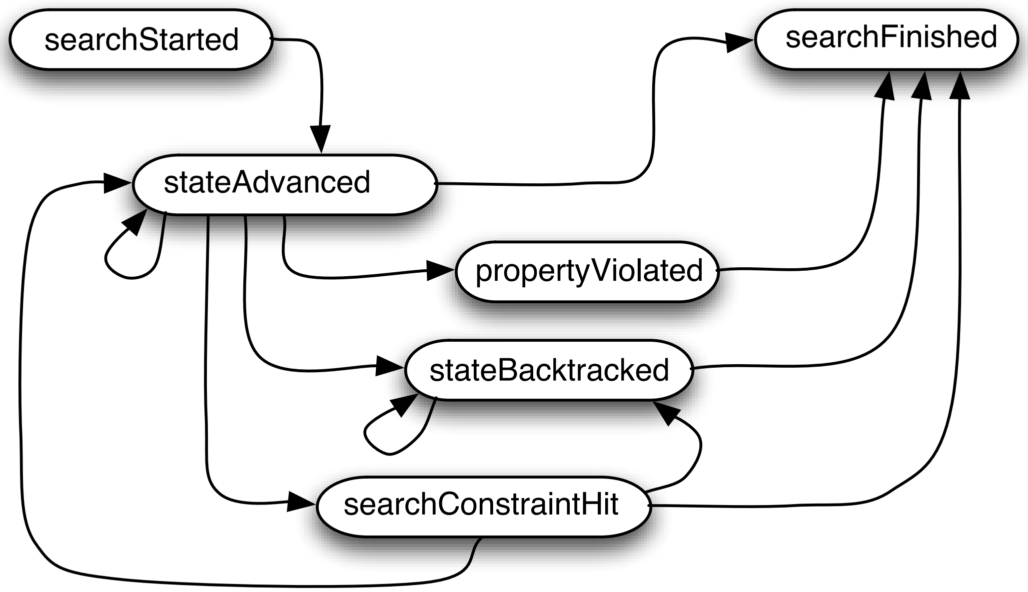
Extending JPF - Listeners

- preferred way of extending JPF: ‘Listener’ variant of the Observer pattern - keep extensions out of the core classes
- listeners can subscribe to Search and VM events



Extending JPF - SearchListener

```
public interface SearchListener {

  /* got the next state */
  void stateAdvanced (Search search);

  /* state was backtracked one step */
  void stateBacktracked (Search search);

  /* a previously generated state was restored
     (can be on a completely different path) */
  void stateRestored (Search search);

  /* JPF encountered a property violation */
  void propertyViolated (Search search);

  /* we get this after we enter the search loop, but BEFORE the first forward */
  void searchStarted (Search search);

  /* there was some contraint hit in the search, we back out could have been turned
     into a property, but usually is an attribute of the search, not the application */
  void searchConstraintHit (Search search);

  /* we're done, either with or without a preceeding error */
  void searchFinished (Search search);
}
```



Extending JPF - VMListener

```
public interface VMListener {

  void instructionExecuted (VM vm);  // VM has executed next instruction

  void threadStarted (VM vm);        // new Thread entered run() method

  void threadTerminated (VM vm);     // Thread exited run() method

  void classLoaded (VM vm);          // new class was loaded

  void objectCreated (VM vm);        // new object was created

  void objectReleased (VM vm);       // object was garbage collected

  void gcBegin (VM vm);              // garbage collection mark phase started

  void gcEnd (VM vm);                // garbage collection sweep phase terminated

  void exceptionThrown (VM vm);      // exception was thrown

  void nextChoice (VM vm);           // choice generator returned new value

}
```

Extending JPF - Listener Example

```
public class HeapTracker
                   extends GenericProperty implements VMListener, SearchListener {
  class PathStat { .. int heapSize = 0; .. }        // helper to store additional state info

  PathStat stat = new PathStat();
  Stack pathStats = new Stack();

  public boolean check (VM vm, Object arg) {        // GenericProperty
    return (stat.heapSize <= maxHeapSizeLimit);
  }
  public void stateAdvanced (Search search) {       // SearchListener
    if (search.isNewState()) {..
      pathStats.push(stat);
      stat = (PathStat)stat.clone(); ..
  }
  public void stateBacktracked (Search search) {    // SearchListener
    .. if (!pathStats.isEmpty())  stat = (PathStat) pathStats.pop();
  }
  public void objectCreated (VM vm) {..             // VMListener
    ElementInfo ei = ((JVM)vm).getLastElementInfo();
    ..stat.heapSize += ei.getHeapSize(); ..
  }
  public void objectReleased (VM vm) {              // VMListener
    ElementInfo ei = ((JVM)vm).getLastElementInfo();
    ..stat.heapSize -= ei.getHeapSize(); ..
  }
  ...
}
```

Extending JPF - Listener Configuration

- listeners are usually configured, not hard coded
- per configuration file:

```
search.listener = MySearchListener
vm.listener = MyVMListener
jpf.listener = MyCombinedListener:MySecondListener...
```

- per command line:

```
jpf ... +jpf.listener=MyCombinedListener  ...
```

- hard coded:

```
MyListener listener= new MyListener(..);
..
Config config = JPF.createConfig( args);
JPF jpf = new JPF( config);
jpf. addSearchListener (listener);
jpf. addVMListener ( listener);
jpf.run();
..
```

Extending JPF - Properties

- dedicated check objects that are configured into the Search (checked after each new transition)
- simple interface:

```
public interface Property extends Printable {
   boolean check (VM vm, Object arg);
   String getErrorMessage();
}
```

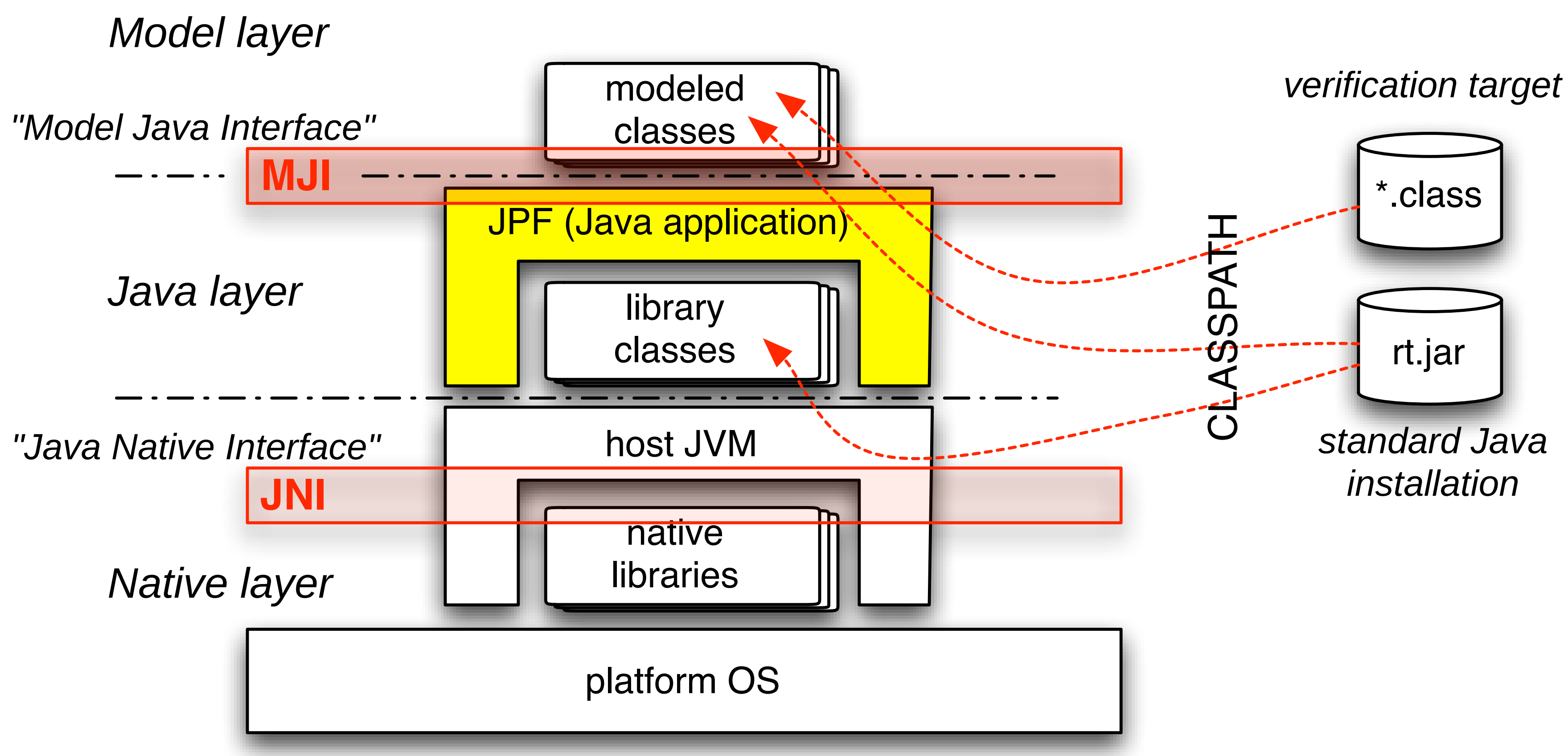
- JPF includes a number of non-functional Property implementations:
  - NotDeadlockedProperty
  - NoUncaughtExceptionsProperty
- configured via search.properties:

```
search.properties = gov.nasa.jpf.jvm.NotDeadlockedProperty:...:x.y.z.MyProperty
```

- generic way to introduce functional properties: Java assertions (->AssertionError -> NoUncaughtExceptionsProperty)
- more complex: listeners that also implement Property (HeapTracker)
- even more complex: DynamicAssertions ("assertions with state" - check objects which are state tracked by JPF)

Going Native - Model Java Interface

- JPF is a state-tracking JVM, running on top of a general JVM
- *Java Native Interface* (JNI) analogy: "execute one level lower"
- *Model Java Interface* (MJI): execute in the host VM that runs JPF itself



MJI - Why?

- one obvious reason: running native Java methods in JPF (otherwise we couldn't run apps using standard libraries, which have lots of native methods)
- more general: replace methods
- specific use of native methods: interface library methods to JPF runtime system (e.g. java.lang.Thread -> ThreadInfo)
- enables usage of specialized verification API in app, interfacing to JPF functionality:

```
int input = gov.nasa.jpf.jvm.Verify.randomInt(10);
```

- but also useful for scalability reasons
  - native methods can save state space
  - native methods are executed atomically
  - native methods execute much faster
- example: java.io.RandomAccessFile

MJI - Components

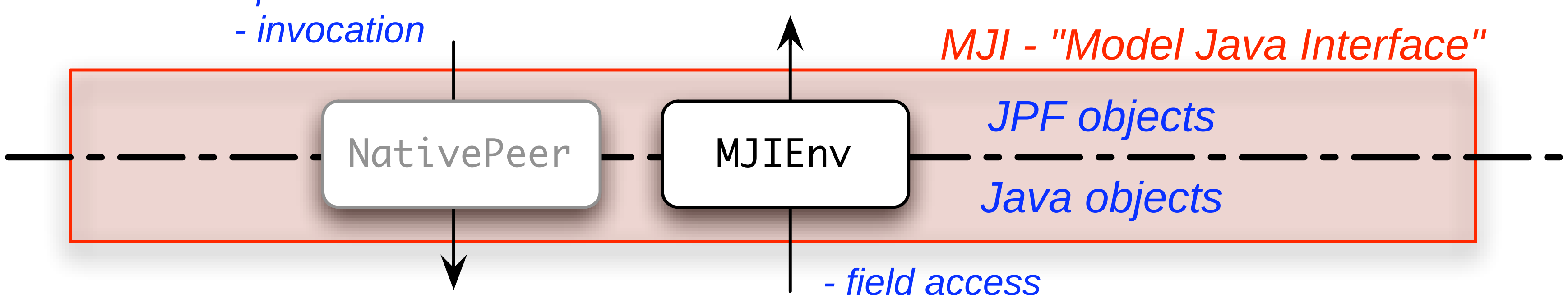
- **Model** class: has native method declaration, executed by JPF
- **NativePeer** class: native method implementation, executed by JVM
- **MJIEnv**: native method calling context (to get back to JPF)

"Model" Class

JPF Class

```
package x.y.z;
class MyClass {
  ..
  native String foo (int i, String s);
}
```

- method lookup
- parameter conversion
- invocation



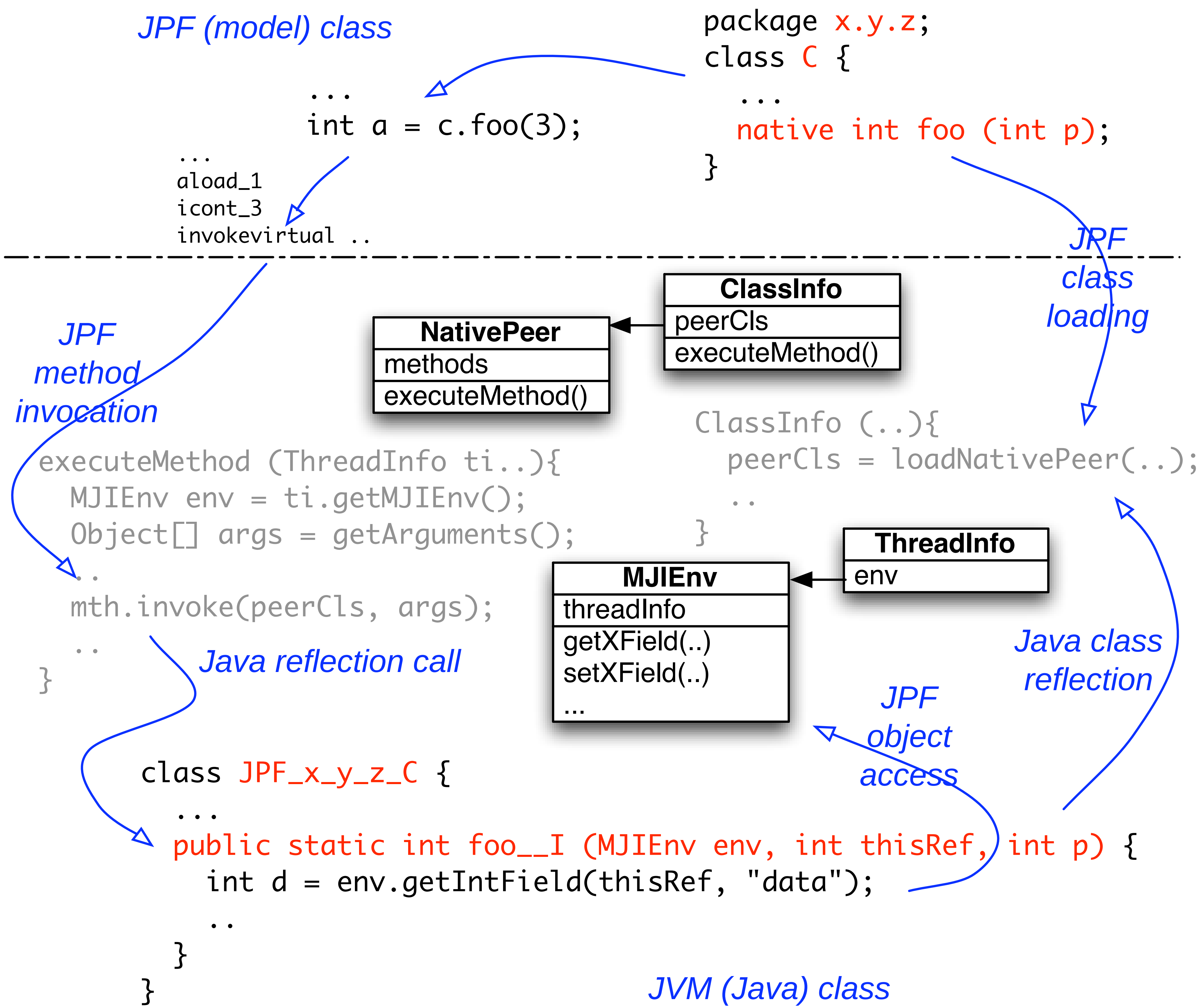
- field access
- object conversion
- JPF intrinsics access

```
class JPF_x_y_z_MyClass {
  public static
      int foo__ILjava_lang_String__2 (MJIEnv env, int objRef,
                                      int i, int sRef) {
    String s = env.getStringObject(sRef);
    ..
    int ref = env.newString(..);
    return ref;
  }
}
```

Java Class

"NativePeer" Class

MJI - How



JPF (model) class
package x.y.z;
class C {
...
native int foo (int p);
}
...
int a = c.foo(3);
...
aload_1
icont_3
invokevirtual ..
JPF class loading
JPF method invocation
ClassInfo
peerCls
executeMethod()
NativePeer
methods
executeMethod()
ClassInfo (..){
peerCls = loadNativePeer(..);
..
}
executeMethod (ThreadInfo ti..){
MJIEnv env = ti.getMJIEnv();
Object[] args = getArguments();
..
mth.invoke(peerCls, args);
..
}
ThreadInfo
env
MJIEnv
threadInfo
getXField(..)
setXField(..)
...
Java reflection call
Java class reflection
JPF object access
class JPF_x_y_z_C {
...
public static int foo__I (MJIEnv env, int thisRef, int p) {
int d = env.getIntField(thisRef, "data");
..
}
}
JVM (Java) class

MJI - Example

- application calls method to intercept

```
..
System.out.println("a message");
```

```
0:    getstatic #2
3:    ldc #3
5:    invokevirtual #4
```

- model class declares the method we want to intercept (doesn't have to be native), is executed by JPF

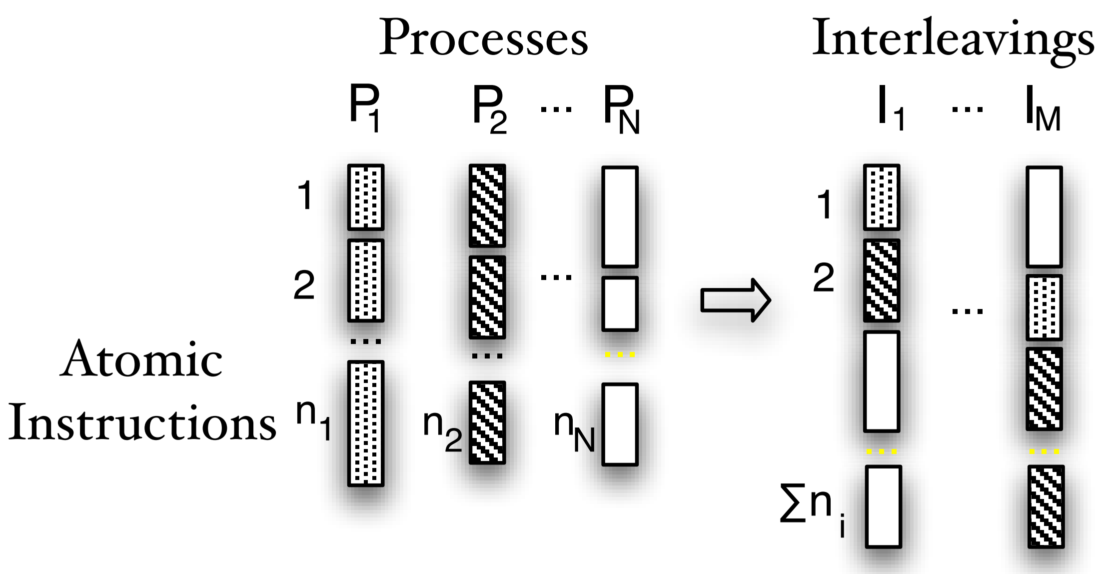
```
public class PrintStream .. {
  ..
  public void println (String s) {..}  // usually native method
}
```

- native peer has the method implementation that gets executed by host VM (not simulated by JPF)

```
class JPF_java_io_PrintStream { ..
  public static void println__Ljava_lang_String_2 (MJIEnv env,int objRef,
                                                  int strRef) {
    env.getVM().println(env.getStringObject(strRef));
  }
}
```

Scalability - Partial Order Reduction

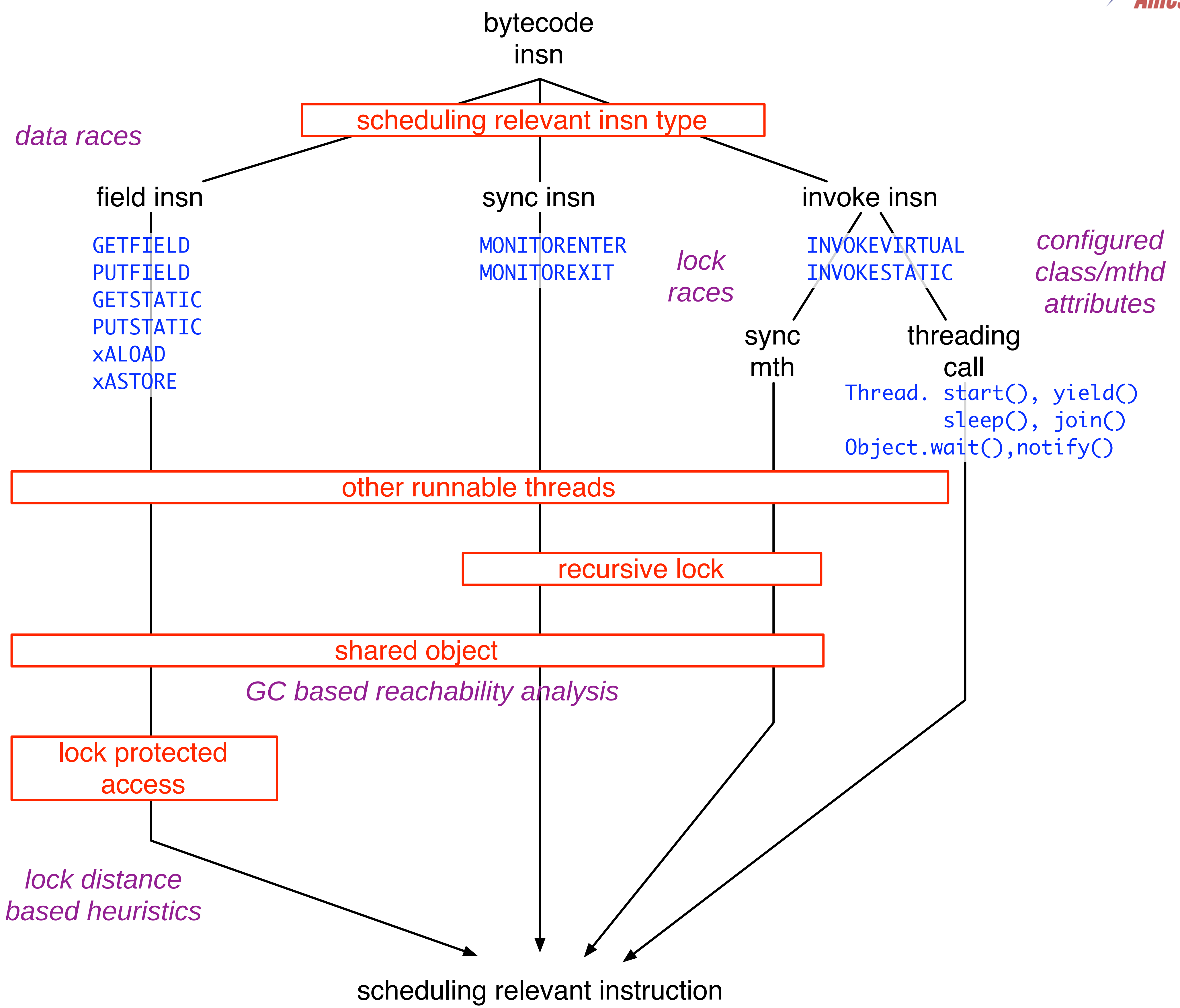
- concurrency is major contributor to state space explosion



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

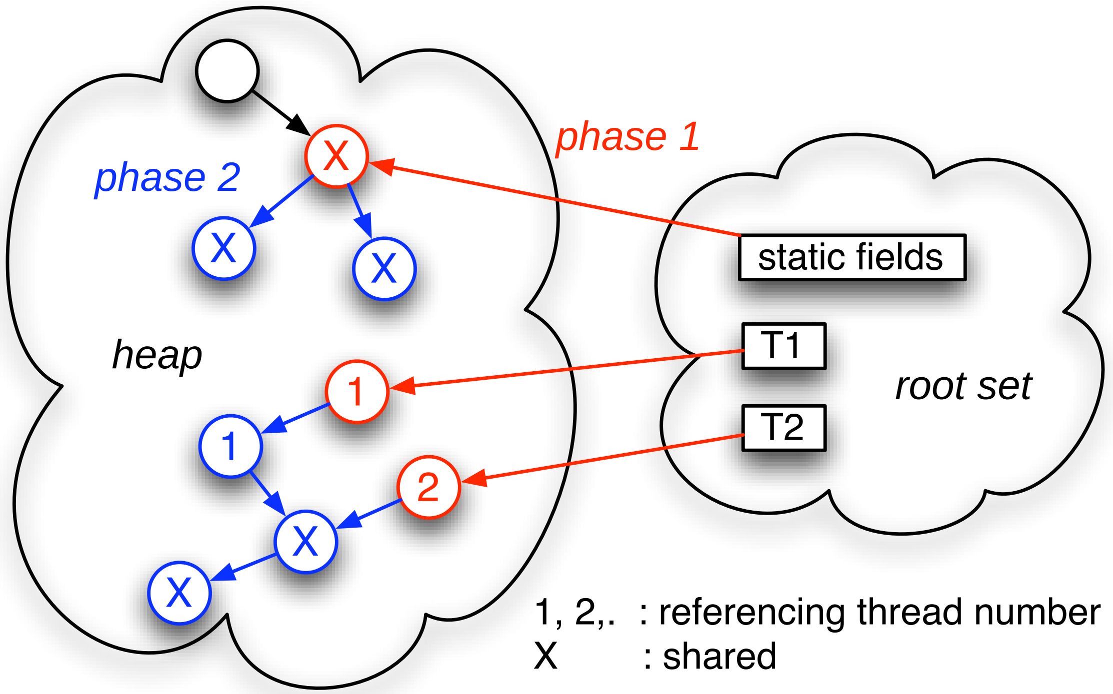
- reduction of thread interleavings is paramount for scalability
- JPF employs on-the-fly *Partial Order Reduction* mechanism
- leveled approach that makes use of JVM instruction set and infrastructure (memory management)
- completely at runtime (on-the-fly)

POR - Scheduling Relevance



POR - Shared Objects

- to detect races, we have to identify read/write access to objects that are visible from different threads
- expensive operation, BUT: can piggyback on garbage collection
- two phase approach:
  - mark root set with thread id (statics are shared by default)
  - traverse marked objects - if another thread id is reached, mark as shared



- problem: GC based on reachability, not accessibility -> need to break on certain fields (Thread.group->ThreadGroup.threads)

A Glimpse into the Future - ChoiceGenerator

- two types of execution path variation in JPF: scheduling sequences and nondeterministic data values
- nondeterministic input (test driver) via gov.nasa.jpf.jvm.Verify API

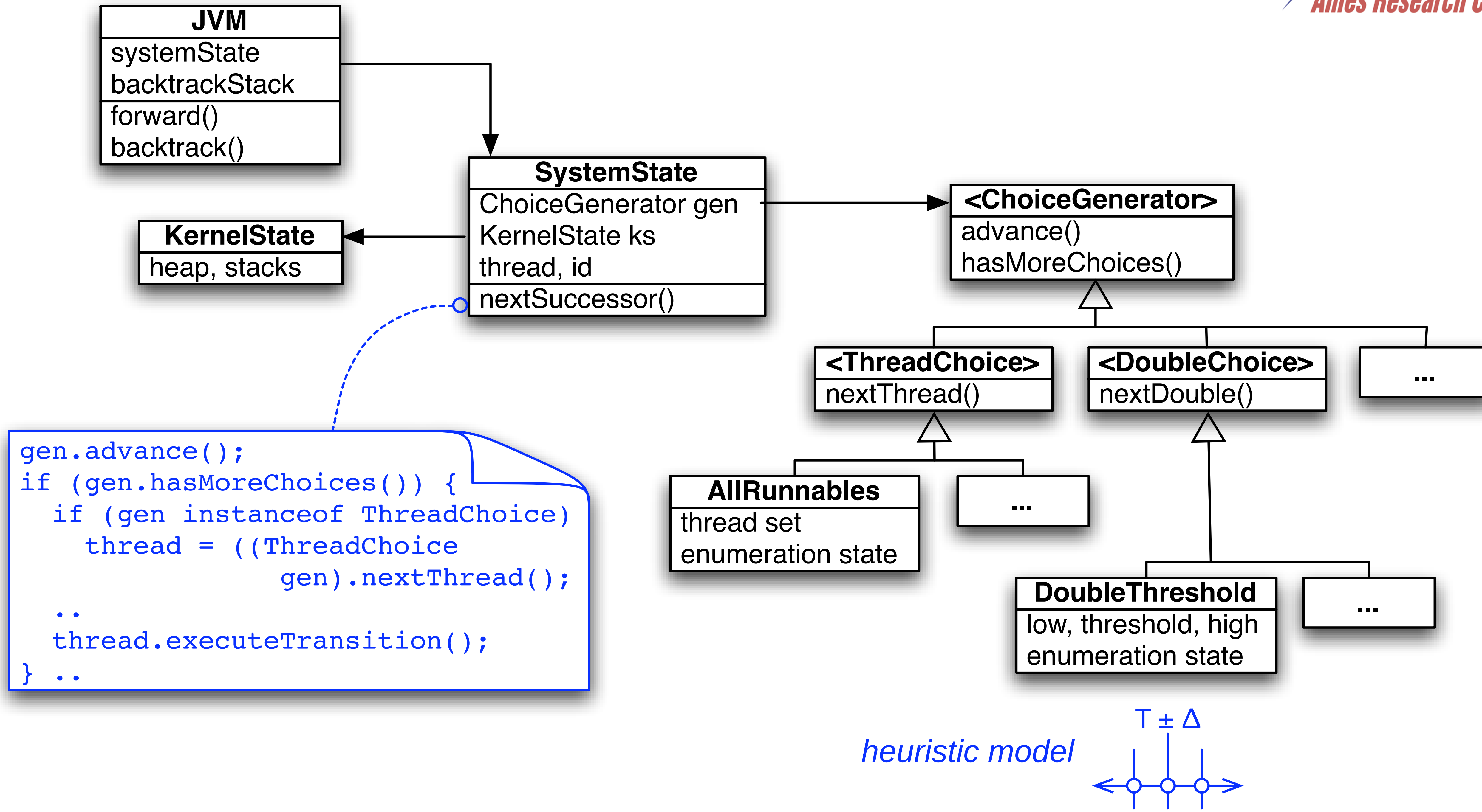
```
int a = Verify.random(2);  // will execute for {0,1,2}
```

  what about partial enumerations (app-specific double value sets)

```
double velocity = Verify.getDouble("v"); // {v0, vT, v1}
```

- scheduling has to cover runnable set and order - will become more challenging with Realtime Java (programmable, deterministic scheduler)
- current gov.nasa.jpf.jvm.Scheduler implementations: not very extensible, has structural overhead (thread/random int values, intermediate kernel states, partial value sets have to be implemented in app)
- goal: unify nondeterministic data and scheduling: ChoiceGenerators

ChoiceGenerators



test application code

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

configuration mode property file)

```
velocity.class = DoubleThreshold
velocity.threshold = 13250
velocity.delta = 500
```