

Byteman

Programmer's Guide

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Introduction to Byteman

Byteman is a bytecode manipulation tool which makes it simple to change the operation of Java applications either at load time or while the application is running. It works without the need to rewrite or recompile the original program. In fact, Byteman can even be used to modify Java code which forms part of the Java virtual machine, classes such as String, Thread etc. Byteman employs a clear, simple and easy-to-use Event Condition Action (ECA) rule language, based on Java. ECA rules are used to specify where, when and how the original Java code should be transformed to modify its operation.

Byteman was invented primarily to support automation of tests for multi-threaded and multi-JVM Java applications using a technique called fault injection. It includes features which have been designed to resolve problems which arise with this type of testing.

Byteman provides explicit support for test automation in four main areas:

- tracing execution of specific code paths and displaying application or JVM state
- subverting normal execution by changing state, making unscheduled method calls or forcing an unexpected return or throw
- orchestrating the timing of activities performed by independent application threads
- monitoring and gathering statistics summarising application and JVM operation

Byteman is actually of much more general use than as a tool for testing. The core engine which underlies Byteman is a general purpose code injection program capable of injecting rule code into almost any location reachable during execution of a Java method. Byteman rule conditions and actions can employ all the normal Java built-in operations in order to test and modify program state. They can also invoke methods of application or JVM instances which are in scope at the injection point.

The Byteman rule language provides a standard set of built-in operations which support specific tasks from the categories outlined above. For example, a rule condition may enforce a wait on a thread rendezvous or an action may update a statistical counter. The available set of built-in calls is configured using a POJO plugin. This can easily be replaced with an alternative implementation either for a set of rules or on a piecemeal basis for individual rules. This makes it trivial to modify and/or extend the rule language to support ad-hoc program modifications which are specific to the application domain.

Running an Application with the Byteman Agent

In order to use Byteman to test a Java application the JVM must be configured to load and run the Byteman rule engine. At the most basic level this can be achieved using the `-javaagent` command line argument. The trailing text appended to this argument points the JVM at a jar containing the Byteman rule engine. It may also identify the location of one or more Byteman rule scripts, files comprising a sequence of ECA rules specifying the side-effects to be introduced into the application under test. The engine reads these scripts when the application is launched and applies the rules to any code which matches a rule in the supplied scripts. Command scripts are provided to simplify the task of loading the agent and installing rules into your program.

In order to simplify test automation Byteman has been integrated with the two popular testing frameworks JUnit and TestNG, allowing Byteman tests to be driven from either ant or Maven. Using the integration modules fault injection testing involves no more than annotating your program with suitable rules and ensuring that the Byteman jars are located in the classpath.

If your Java application is a long-running program then you may want to load the rule scripts and, possibly even, the rule engine after the program has started running. For example, you may decide to install Byteman into your application server when it appears to be suffering from performance problems and only then upload rules which trace execution of the code you suspect is misbehaving. Once the rule engine is loaded it cannot be unloaded. However, rules can be added and removed ad lib, allowed you to focus in on the problem in hand using more and more specific trace or monitoring rules. Note that when rules are removed the methods they affect are guaranteed to return to their original behaviour.

Full details of how to install the Byteman agent and how to upload rules either at boot time or at runtime are provided in subsection Running Applications with Byteman. Full examples of how to use Byteman from the command line, plus examples of how to configure annotation based fault injection testing from ant or Maven project, are available in the online tutorials which are linked from the documentation page of the Byteman site <http://www.jboss.org/byteman>.

Event Condition Action Rules

The Byteman rule engine operates by introducing side-effects at specified points during execution. A Byteman script comprises a sequence of Event Condition Action (ECA) rules which specify precisely how the application behaviour should be transformed at runtime. The three components of these rules, event, condition and action, are used, respectively, to define:

- *where* during application execution a side-effect should occur
- *whether* the side-effect should happen or not
- *what* the side effect should be

For example, in the following example rule the event is defined by the CLASS, METHOD and AT INVOKE clauses. It specifies a trigger point in method `get()` of class `BoundedBuffer`. The example assumes that the definition of method `get()` includes a call to `Object.wait()`. This would be appropriate if, say, the buffer were empty. The location specifier AT INVOKE places the trigger point just before the call to this method.

```
RULE throw on Nth empty get
CLASS org.my.BoundedBuffer
METHOD get()
AT INVOKE Object.wait()
BIND buffer = $this
IF countDown(buffer)
DO throw new org.my.ClosedException(buffer)
ENDRULE
```

The event also includes a BIND clause which establishes a binding for local variable `buffer` assigning it with the value `$this` (a rather artificial thing to do but this *is* an example). `$this` is an automatic binding which refers to the target of the `get()` call which triggered the rule. `buffer` can be referred to later in the rule; in this case it is passed as an argument to the exception constructor in the DO clause.

The condition is defined by the IF clause. It invokes the standard Byteman built-in `countDown(Object)` which decrements a `CountDown` associated with the `buffer` — the example assumes some other rule has called `createCountDown(buffer, N)` to create this `CountDown` and initialise it with value `N`. The `countDown` built-in returns true when the

value of the `CountDown` decrements to zero.

The action is defined by the `DO` clause. It causes an instance of `ClosedException` to be created and thrown from the `get ()` call which triggered the rule.

So, in this example the condition will evaluate to `false` the first `N-1` times that a getter attempts to wait. At the `N`th triggering the condition will evaluate to `true` and the rule will fire, running the built-in action `throw`. This will cause the triggering thread to throw a `ClosedException` to the caller of method `get ()`.

Rule Bindings and Parameterization

The corresponding rule to set up the `countDown` might be defined as follows

```
RULE set up buffer countDown
CLASS org.my.BoundedBuffer
METHOD <init>(int)
AT EXIT
BIND buffer = $0;
    size = $1
IF $1 < 100
DO createCountDown(buffer, size - 1)
ENDRULE
```

This rule is attached to the constructor for class `BoundedBuffer` which takes a single `int` parameter. The `AT EXIT` location means it is triggered just before the constructor returns. The `BIND` clause employs the indexed notation to refer to the method target, `$0`, and the first argument `$1`. The latter is assumed for the sake of the example to be the buffer size. If the buffer size is less than 100 then the rule creates a `countDown` with `count size - 1` using the buffer as a key to identify it.

Notice how the parameterization of the `createCountDown` and `countDown` calls with the bound variable `buffer` restricts the scope of these rules to specific cases. If there are two buffers, `buffer1` and `buffer2`, but only `buffer1` has size less than 100 then the condition for the set up rule will return `false` when `buffer2` is created. This means the action will not run and a `countDown` will not be associated with `buffer2`. When a subsequent call is made to `buffer2.get ()` the throw rule will be triggered but the condition will always return `false` and the rule will not fire.

If instead both buffers have size less than 100 then two `countDown`s will be created. The throw rule will be triggered when either `buffer1.get ()` and `buffer2.get ()` is called and in both cases will eventually fire and throw an exception. However, each `countDown` will still decrement independently.

Built-in Conditions and Actions

Byteman provides a suite of built-in conditions and actions used to coordinate the activities of independent threads e.g. delays, waits and signals, countdowns, flag operations and so on. These are particularly useful for testing multi-threaded programs subject to arbitrary scheduling orders. Judicious insertion of byteman actions can guarantee that thread interleavings in a given test run will occur in a desired order, enabling test code to reliably exercise parallel execution paths which do not normally occur with synthetic workloads.

Tracing operations are also provided so that test scripts can track progress of a test run and identify successful or unsuccessful test completion. Trace output can also be used to

debug rule execution. Trace output to be quite finely tuned simply by providing a condition which tests the state of local or parameter variable bindings. Trace actions can insert these bound values into message strings, allowing detailed scrutiny of test execution paths.

A few special built-in actions can be used to subvert the behaviour of application code by modifying execution paths. This is particularly important in a test environment where it is often necessary to force application methods to generate dummy results or simulate an error.

A *return* action forces an early return from the code location targeted by the rule. If the method is non-void then the return action supplies a value to use as the method result.

A *throw* action enables exceptions to be thrown from the trigger method frame. A rule is always allowed to throw a runtime exception (i.e. instances of `RuntimeException` or its subclasses). If none of the caller methods up the stack from the trigger method include a catch for `RuntimeException` or `Throwable` then effectively this aborts the current thread. Other exceptions may also be thrown so long as the trigger method declares the exception in its throws list. This restriction is necessary to ensure that the injected code does not break the method contract between the trigger method and its callers.

Finally, a call to the *killJVM* builtin allows a machine crash to be simulated by configuring an immediate exit from the JVM.

It is worth noting that rules are not just restricted to using built-in operations. Application-specific side-effects can also be introduced by writing object fields or calling Java methods in rule events, conditions or actions. The obvious target for such field write or method call operations is objects supplied from the triggering method via local or parameter variable bindings. However, it is also possible to update static data and invoke static methods of any class accessible from the classloader of the triggering method. So, it is quite feasible to use Byteman rules to apply arbitrary modifications to the original program. Byteman rules have special access privileges which means that it is possible to read and write protected or private fields and call protected or private data.

Extending or Replacing the Byteman Language Built-ins

Another option to bear in mind is that the set of built-in operations available to Byteman rules is not fixed. The rule engine works by mapping built-in operations which occur in a given rule to public instance methods of a helper class associated with the rule. By default, this helper class is `org.jboss.byteman.rule.helper.Helper`, which provides the standard set of built-ins designed to simplify management of threads in a multi-threaded application. For example, the builtin operations `createCountDown()` and `countDown()` used in the example rules provided above are just public methods of class `Helper`. The set of built-ins available for use in a given rule can be changed merely by specifying an alternative helper class for that rule.

Any non-abstract class may be specified as the helper. Its public instance methods automatically become available as built-in operations in the rule event, condition and action. For example, by specifying a helper class which extended the default class, `Helper`, a rule would be able to use any of the existing built-ins and/or also make rule-specific (or application-specific) built-in calls. So, although the default Byteman rule language is oriented towards orchestrating the behaviour of independent threads in multi-threaded tests, Byteman can easily be reconfigured to support a much wider range of application requirements.

Agent Transformation

The bytecode modifications performed by ByteMan are implemented using a *Java agent* program. JVM class loaders provide agents with an opportunity to modify loaded bytecode just prior to compilation (see package `java.lang.Instrumentation` for details of how Java agents work). The ByteMan agent reads the rule script at JVM bootstrap. It then monitors method code as it is loaded looking for *trigger points*, locations in the method bytecode which match the locations specified in rule events.

The agent inserts *trigger calls* into code at each point which matches a rule event. Trigger calls are calls to the rule execution engine which identify:

- the *trigger method*, i.e. the method which contains the trigger point
- the rule which has been matched
- the arguments to the trigger method

If several rules match the same trigger point then there will be a sequence of trigger calls, one for each matching rule. In this case rules are mostly triggered in the order they appear in their script(s). The only exception is rules which specify an AFTER location, such as AFTER READ `myField` or AFTER INVOKE `someMethod`, which are executed in reverse order of appearance.

When a trigger call occurs the rule execution engine locates the relevant rule and then executes it. The rule execution engine establishes bindings for variables mentioned in the rule event and then *tests* the rule condition. If the condition evaluates to true it *fires* the rule, executing each of the rule actions in sequence.

Trigger calls pass the method recipient (`this`) and method arguments to the rule engine. These values may be referred to in the condition and action with a standard naming convention, `$0`, `$1` etc. The event specification can introduce bindings for additional variables. Bindings for these variables may be initialized using literal data or by invoking methods or operations on the method parameters and/or static data. Variables bound in the event can simply be referred to by name in the condition or action. Bindings allow arbitrary data from the triggering context to be tested in the condition in order to decide whether to fire the rule and to be employed as a target or parameter for rule actions. Note that where the trigger code is compiled with the relevant debug options enabled the agent is able to pass local variables which are in scope at the trigger point as arguments to the trigger call, making them available as default bindings. Rules may refer to in-scope variables (including the method recipient and arguments) by prefixing their symbolic names with the `$` character e.g. `$this`, `$arg1`, `$i` etc.

The agent also compiles exception handler code around the trigger calls in order to deal with exceptions which might arise during rule processing. This is not intended to handle errors detected during operation of the rule execution engine (they should all be caught and dealt with internally). Exceptions are thrown out of the execution engine to alter the flow of control through the triggering method. Normally, after returning from a trigger call the triggering thread continues to execute the original method code. However, a rule can use the `return` and `throw` built-in actions to specify that an early return or exception throw should be performed *from the trigger method*. The rule language implementation achieves this by throwing its own private, internal exceptions below the trigger call. The handler code compiled into the trigger method catches these internal exceptions and then either returns to the caller or recursively throws a runtime or application-specific exception. This avoids normal execution of the remaining code in the body of the triggering method. If there are other trigger calls pending at the trigger point then these are also bypassed when a `return` or `throw` action is executed.

Agent Retransformation

The agent also allows rules to be uploaded while the application is still running. This can be used to redefine previously loaded rules as well as to introduce new rules on the fly. In cases where no currently loaded class matches the uploaded rule the agent merely adds the new rule to the current rule set. This may possibly replace an earlier version of the rule (rules are equated if they have the same name). When a matching class is loaded the latest version of the rule will be used to transform it.

In cases where there are already loaded classes which match the rule the agent will retransform them, modifying the relevant target methods to include any necessary trigger calls. If an uploaded rule replaces an existing rule in this situation then when the previous rule is deleted all trigger calls associated with it are removed from the affected target methods. Note that retransforming a class does not associate a new class object with existing instances of the class. It merely installs a different implementation for their methods.

An important point where retransformation may occur automatically without an explicit upload is during bootstrap of the agent. The JVM needs to load various of its own bootstrap classes before it can start the agent and allow it to register a transformer. Once the agent has processed the initial rule set and registered a transformer it scans all currently loaded classes and identifies those which match rules in the rule set. It automatically retransforms these classes, causing subsequent calls to bootstrap code to trigger rule processing.

ECA Rule Engine

The Byteman rule execution engine consists of a rule parser, type checker and interpreter/compiler. The rule parser is invoked by the agent during bootstrap. This provides enough information to enable the agent to identify potential trigger points.

Rules are not type checked and compiled during trigger injection. These steps are delayed until the class and method bytecode they refer to has been loaded. Type checking requires identifying properties of the trigger class and, potentially, of classes it mentions using reflection. To do this the type checker needs to identify properties of loaded classes such as the types and accessibility of fields, method signatures etc. So, in order to ensure that the trigger class and all its dependent classes have been loaded before the type checker tries to access them, rules are type checked and compiled the first time they are triggered. This also avoids the cost of checking and compiling rules included in the rule set which do not actually get called.

A single rule may be associated with more than one trigger point. Firstly, depending upon how precisely the rule specifies its event, it may apply to more than one class or more than one method within a class. But secondly, even if a rule specifies a class and method unambiguously the same class file may be loaded by different class loaders. So, the rule has to be type checked and compiled for each applicable trigger point.

If a type check or compile operation fails the rule engine prints an error and disables execution of the trigger call. Note that in cases where the event specification is ambiguous a rule may type check successfully against one trigger point but not against another. Rule execution is only disabled for cases where the type check fails.

In the basic operating mode, trigger calls execute a rule by interpreting the rule parse tree. It is also possible to configure the rule engine to translate the rule bindings, condition and actions to bytecode which can then be passed by the JIT compiler. In either case, execution is performed with the help of an auxiliary class generated at runtime by the

Byteman agent called a *helper adapter*. This class is actually a subclass of the helper class associated with the rule. It inherits from the helper class so that it knows how to execute built-in operations defined by the helper class. A subclass is used to add extra functionality required by the rule system, most notably method `execute` which gets called at the trigger point and a local bindings field which stores a hashmap mapping method parameters and event variables to their bound values.

When a rule is triggered the rule engine creates an instance of the rule's helper adapter class to provide a context for the trigger call. It uses setter methods generated by the Byteman agent to initialise the rule and bindings fields and then it calls the adapter instance's `execute` method. Since each rule triggering is handled by its own adapter instance this ensures that concurrent triggers of the same rule from different threads do not interfere with each other.

The interpreted version of `execute` locates the triggered rule and, from there, the parse tree for the event, condition and action. It traverses the parse trees of these three rule components evaluating each expression recursively. Bindings are looked up or assigned during rule execution when they are referred to from within the rule event, condition or action. When the `execute` method encounters a call to a built-in it can execute this call using reflection to invoke one of the methods inherited from its helper superclass.

When compilation of rules is enabled the Byteman agent generates an `execute` method which contains inline bytecode derived from the rule event condition and action. This directly encodes all the operations and method invocations defined in the rule. This code accesses bindings and executes built-ins in the same way as the interpreted code except that calls to built-in are compiled as direct method invocations on this rather than relying on reflective invocation.

Although compilation takes slightly more time to generate it should provide a performance pay off where the trigger method gets called many times. Ideally, compilation should be selectable per rule or across the board for all rules in a rule set. At present it can only be enabled or disabled globally.

The Byteman Rule Language

Rules are defined in scripts which consists of a sequence of rule definitions interleaved with comment lines. Comments may occur within the body of a rule definition as well as preceding or following a definition but must be on separate lines from the rule text. Comments are lines which begin with a # character:

```
#####  
# Example Rule Set  
#  
# a single rule definition  
RULE example rule  
# comment line in rule body  
.  
.  
.  
ENDRULE
```

Rule Events

Rule event specifications identify a specific *location* in a *target* method associated with a *target* class. Target methods can be either static or instance methods or constructors. If no detailed location is specified the default location is entry to the target method. So, the basic schema for a single rule is as follows:

```
# rule skeleton  
RULE <rule name>  
CLASS <class name>  
METHOD <method name>  
BIND <bindings>  
IF <condition>  
DO <actions>  
ENDRULE
```

The name of the rule following the RULE keyword can be any free form text with the restriction that it must include at least one non-white space character. Rule names do not have to be unique but it obviously helps when debugging rule scripts if they clearly identify the rule. The rule name is printed whenever an error is encountered during parsing, type checking, compilation or execution.

The class and method names following the CLASS and METHOD keywords must be on the same line. The class name can identify a class either with or without the package qualification. The method name can identify a method with or without an argument list or return type. A constructor method is identified using the special name <init>. For example,

```
# class and method example  
RULE any commit on any coordinator engine  
CLASS CoordinatorEngine  
METHOD commit  
.  
.  
.  
ENDRULE
```

matches the rule with any class whose name is CoordinatorEngine, irrespective of the package it belongs to. When any class with this name is loaded then the agent will insert a trigger point at the beginning of any method named commit. If there are several occurrences of this method, with different signatures then each method will have a trigger point inserted.

More precise matches can be guaranteed by adding a signature comprising a parameter type list and, optionally, a return type. For example,

```
# class and method example 2
RULE commit with no arguments on wst11 coordinator engine
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD State commit()
AT LINE 324
. . .
ENDRULE
```

This rule will only match the `CoordinatorEngine` class in package `com.arjuna.wst11.messaging.engines` and only match a method `commit` with no arguments and with a return type whose name is `State`. Note that in this example the package for class `State` has been left unspecified. The type checker will infer the package of the parameter or return type from the matched method where it is omitted.

The previous example also employs the location specifier `AT LINE`. The text following the line keyword must be able to be parsed to derive an integer line number. This directs the agent to insert the trigger call at the start of a particular line in the source code.

Note:

- The Byteman agent *will not* transform any classes in package `java.lang` nor classes in package `org.jboss.byteman`, the byteman package itself (it is possible to remove the first of these restrictions by setting a System property, but you need to be really sure you know what you are doing – see below for details).
- Inner classes can be specified by employing the (internal format) '\$' separator to distinguish an inner class from its enclosing outer class e.g. `org.my.List$Cons`, `Map$Entry$Wrapper`.

Class Rules vs Interface Rules

Byteman rules can be attached to interfaces as well as classes. If the `CLASS` keyword is replaced with the keyword `INTERFACE` then the rule applies to any class which implements the specified interface. For example, the following rule

```
# interface rule example
RULE commit with no arguments on any engine
INTERFACE com.arjuna.wst11.messaging.engines.Engine
METHOD commit()
. . .
ENDRULE
```

is attached to method `commit` of interface `Engine`. If `Engine` is implemented by classes `CoordinatorEngine` and `ParticipantEngine` then the rule implies two trigger points, one at the start of method `CoordinatorEngine.commit()` and another at the start of method `ParticipantEngine.commit()`. The agent ensures that each implementing class is transformed to include a trigger call for the rule.

Overriding Rules

Normally, Byteman only injects rule code into methods which are defined by the class identified in the `CLASS` clause. This is sometimes not very helpful. For example, the following rule is not much use

```

RULE trace Object.finalize
CLASS java.lang.Object
METHOD finalize
IF TRUE
DO System.out.println("Finalizing " + $0)
DONE

```

The print statement gets inserted into method `Object.finalize()`. However, the JVM only calls `finalize` when an object's class overrides `Object.finalize()`. But with this rule these overriding methods are not modified. So, the rule will not be triggered in the precise case where the trace would be useful (n.b. this is not quite the full story – overriding method implementations which call `super.finalize()` *will* trigger the rule). There are many other situations where it might be desirable to inject code into overriding method implementations. For example, class `Socket` is specialised by various classes which provide their own implementation of methods `bind`, `accept` etc. So, a rule attached to `Socket.bind()` will not be triggered when the `bind` method of one of these subclasses is called (not unless the subclass method calls `super.bind()`).

Of course, it is always possible to define a specific rule for each overriding class. However, this is tedious and may possibly miss some cases when the code base is changed. So, Byteman provides a simple bit of syntax for specifying that rules should also be injected into overriding implementations.

```

RULE trace Object.finalize
CLASS ^java.lang.Object
METHOD finalize
IF TRUE
DO System.out.println("Finalizing " + $0)
ENDRULE

```

The `^` prefix attached to the class name tells the agent that the rule should apply to implementations of `finalize` defined either by class `Object` or by any class which extends `Object`. This prefix can also be used with interface rules, requiring the agent to inject the rule code into methods of classes which implement the interface and also into overriding methods on subclasses of the implementing classes.

Note that if an overriding method invokes a super method then this style of injection may cause the injected rule code to be triggered more than once. In particular, injecting into constructors (which, inevitably, invoke some form of super constructor) will often result in multiple triggerings of the rule. This is easily avoided by adding a condition to the rule which checks the name of the caller method. So, for example, the rule above would be better rewritten as

```

RULE trace Object.finalize at initial call
CLASS ^java.lang.Object
METHOD finalize
IF NOT callerEquals("finalize")
DO System.out.println("Finalizing " + $0)
DONE

```

This rule uses the built-in method `callerEquals` which can be called with a variety of alternative signatures (described in full below). This version calls `String.equals()` comparing the name of the method which called the trigger method to its `String` argument and returns the result. The condition negates this using the `NOT` operator (another way of writing the Java `!` Operator). So, when an implementation of `finalize` is

called via the finalizer thread's `runFinalizer()` method this condition evaluates to `true` and the rule fires. When it gets called via `super.finalize()` the condition evaluates to `false` and the rule does not fire.

Overriding Interface Rules

The `^` prefix can also be used in combination with `INTERFACE` rules. Normally an interface rule is only injected into classes which directly implement the interface methods. This can mean that a plain `INTERFACE` rule does not always get injected into the classes you are interested in.

For example, class `ArrayList` extends class `AbstractList` which, in turn, implements interface `List`. A rule attached to `INTERFACE List` *will* be considered for injection into `AbstractList` but will *not* be considered for injection into `ArrayList`. This makes sense because `AbstractList` will contain an implementation of every method in `List` (some of these methods may be abstract). So, any methods in class `ArrayList` which re-implement the interface are considered to be overriding methods. However, the `^` prefix can be used to achieve the desired effect. If the rule is attached to `INTERFACE ^List` then it *will* be considered for injection into both `AbstractList` and `ArrayList`.

Note that there is a subtle difference between these cases where a class extends a superclass and those where an interface extends a superinterface. The same class hierarchy can be used as an example to explain how interface extension is treated.

Let's look at the interface `Collection` which is extended by interface `List`. When a rule is attached to `INTERFACE Collection` then it is considered for injection into any class which implements `Collection` and also any class which implements an extension of `Collection`. Since `List` extends `Collection` this means that an implementation class like `AbstractList` will be a candidate for the rule. This is because `AbstractList` is the first class reached down the chain from `Collection` via `List` so it is the first point in the class hierarchy where an implementation can be found for methods of `Collection` (even if it is only an abstract method). Class `ArrayList` will *not* be a candidate for injection because any of its methods which re-implement a method declared by `Collection` will still only *override* a method implemented in `AbstractList`. If you want the rule to be injected into these overriding methods defined in class `ArrayList` then you can do so by attaching the rule to `INTERFACE ^Collection`.

Location Specifiers

The examples above either specified the precise location of the trigger point within the target method to a specific line number using `AT LINE` or defaulted it to the start of the method. Clearly, line numbers can be used to specify almost any point during execution and are easy and convenient to use in code which is not subject to change. However, this approach is not very useful for test automation where the code under test may well get modified. Obviously when code is edited the associated tests need to be revised. But modifications to the code base can easily shift the line numbers of unmodified code invalidating test scripts unrelated to the edits. Luckily, there are several other ways of specifying where a trigger point should be inserted into a target method. For example,

```
# location specifier example
RULE countdown at commit
CLASS CoordinatorEngine
METHOD commit
AFTER WRITE $current
. . .
ENDRULE
```

The name `current` prefixed with a `$` sign identifies a local variable, or possibly a method parameter. In this case, `current` happens to be a local variable declared and initialised at the start of method `CoordinatorEngine.commit` whose type is the enum `State`.

```
public State commit()
{
    final State current ;
    synchronized(this)
    {
        current = this.state ;
        if (current == State.STATE_PREPARED_SUCCESS) {
            . . .
        }
    }
}
```

So, the trigger point will be inserted immediately after the first write operation in the bytecode (`istore`) which updates the stack location used to store `current`. This is effectively the same as saying that the trigger point will occur at the point in the source code where local variable `current` is initialised i.e. the first line inside the `synchronized` block.

By contrast, the following rule would locate the trigger point after the first read from field `recovered`:

```
# location specifier example 2
RULE add countdown at recreate
CLASS CoordinatorEngine
METHOD <init>
AT READ CoordinatorEngine.recovered
. . .
ENDRULE
```

Note that in the last example the field type is qualified to ensure that the write is to the field belonging to an instance of class `CoordinatorEngine`. Without the type the rule would match any read from a field with name `recovered`.

The full set of location specifiers is as follows


```

AT ENTRY
AT EXIT
AT LINE number
AT READ [type .] field [count | ALL ]
AT READ $var-or-idx [count | ALL ]
AFTER READ [ type .] field [count | ALL ]
AFTER READ $var-or-idx [count | ALL ]
AT WRITE [ type .] field [count | ALL ]
AT WRITE $var-or-idx [count | ALL ]
AFTER WRITE [ type .] field [count | ALL ]
AFTER WRITE $var-or-idx [count | ALL ]
AT INVOKE [ type .] method [ ( argtypes ) ] [count | ALL ]
AFTER INVOKE [ type .] method [ ( argtypes ) ][count | ALL ]
AT SYNCHRONIZE [count | ALL ]
AFTER SYNCHRONIZE [count | ALL ]
AT THROW [count | ALL ]

```

If a location specifier is provided it must immediately follow the METHOD specifier. If no location specifier is provided it defaults to AT ENTRY.

An AT ENTRY specifier normally locates the trigger point before the first executable instruction in the trigger method. An exception to this occurs in the case of a constructor method in which case the trigger point is located before the first instruction following the call to the super constructor or redirection call to an alternative constructor. This is necessary to ensure that rules do not attempt to bind and operate on the instance before it is constructed

An AT EXIT specifier locates a trigger point at each location in the trigger method where a normal return of control occurs (i.e. wherever there is an implicit or explicit return but not where a throw exits the method).

An AT LINE specifier locates the trigger point before the first executable bytecode instruction in the trigger method whose source line number is greater than or equal to the line number supplied as argument to the specifier. If there is no executable code at (or following) the specified line number the agent will not insert a trigger point (note that it does not print an error in such cases because this may merely indicate that the rule does not apply to this particular class or method).

An AT READ specifier followed by a field name locates the trigger point before the first mention of an object field whose name matches the supplied field name i.e. it corresponds to the first occurred of a corresponding getField instruction in the bytecode. If a type is specified then the getField instruction will only be matched if the named field is declared by a class whose name matches the supplied type. If a count *N* is supplied then the *N*th matching getField will be used as the trigger point. Note that the count identifies to the *N*th textual occurrence of the field access, not the *N*th field access in a particular execution path at runtime. If the keyword ALL is specified in place of a count then the rule will be triggered at all matching getField calls.

An AT READ specifier followed by a \$-prefixed local variable name, method parameter name or method parameter index locates the trigger point before the first instruction which reads the corresponding local or method parameter variable i.e. it corresponds to an iload, dload, aload etc instruction in the bytecode. If a count *N* is supplied then the *N*th matching read will be used as the trigger point. Note that the count identifies to the *N*th textual occurrence of a read of the variable, not the *N*th access in a particular execution path at runtime. If the keyword ALL is specified in place of a count then the rule will be

triggered before every read of the variable.

Note that it is only possible to use local or parameter variable names such as `$i`, `$this` or `$arg1` if the trigger method bytecode includes a local variable table, e.g. if it has been compiled with the `-g` flag. By contrast, it is always possible to refer to parameter variable read operations using the index notation `$0`, `$1` etc (however, note that location `AT READ $0` will only match where the trigger method is an instance method).

An `AFTER READ` specification is identical to an `AT READ` specification except that it locates the trigger point after the `getField` or variable read operation.

`AT WRITE` and `AFTER WRITE` specifiers are the same as the corresponding `READ` specifiers except that they correspond to assignments to the named field or named variable in the source code i.e. they identify `putField` or `istore`, `dstore`, etc instructions.

Note that location `AT WRITE $0` or, equivalently, `AT WRITE $this` will never match any candidate trigger method because the target object for an instance method invocation is never assigned.

Note also that for a given local variable, `localvar`, location `AT WRITE $localvar` or, equivalently, `AT WRITE $localvar 1` identifies the location immediately *after* the local variable is initialised i.e. it is treated as if it were specified as `AFTER WRITE $localvar`. This is necessary because the variable is not in scope until after it is initialised. This also ensures that the local variable which has been written can be safely accessed in the rule body.

`AT INVOKE` and `AFTER INVOKE` specifiers are like `READ` and `WRITE` specifiers except that they identify invocations of methods or constructors within the trigger method as the trigger point. The method may be identified using a bare method name or the name may be qualified by a, possibly package-qualified, type or by a descriptor. A descriptor consists of a comma-separated list of type names within brackets. The type names identify the types of the method parameters and may be prefixed with package qualifiers and employ array bracket pairs as suffixes.

`AT SYNCHRONIZE` and `AFTER SYNCHRONIZE` specifiers identify synchronization blocks in the target method, i.e. they correspond to `MONITORENTER` instructions in the bytecode. Note that `AFTER SYNCHRONIZE` identifies the point immediately after entry to the synchronized block rather than the point immediately after exit from the block.

An `AT THROW` specifier identifies a throw operation within the trigger method as the trigger point. The throw operation may be qualified by a, possibly package-qualified, `typename` identifying the lexical type of the thrown exception. If a count *N* is supplied then the location specifies the *N*th textual occurrence of a throw. If the keyword `ALL` is specified in place of a count then the rule will be triggered at all matching occurrences of a throw.

n.b. as mentioned previously, when several rules specify the same location the order of injection of trigger calls usually follows the order of the rules in their respective scripts. The exception to this is `AFTER` locations where the the order of injection is the reverse to the order of occurrence.

n.b.b. when a location specifier (other than `ENTRY` or `EXIT`) is used with an overriding rule the rule code is only injected into the original method or overriding methods if the location matches the method in question. So, for example, if location `AT READ myField 2` is employed then the rule will only be injected into implementations of the method which include two loads of field `myField`. Methods which do not match the location are ignored.

n.b.b.b. for hysterical reasons CALL may be used as a synonym for INVOKE, RETURN may be used as a synonym for EXIT and the AT in an AT LINE specifier is optional.

Rule Bindings

The event specification includes a binding specification which computes values for variables which can subsequently be referenced in the rule body. These values will be computed each time the rule is triggered before testing the rule condition. For example,

```
# binding example
RULE countdown at commit
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
AT READ state
BIND engine:CoordinatorEngine = $0;
    recovered:boolean = engine.isRecovered();
    identifier:String = engine.getId()
. . .
ENDRULE
```

creates a variable called engine. This variable is bound to the recipient of the commit method call which triggered the rule, identified by the parameter reference \$0 (if commit was a static method then reference to \$0 would result in a type check exception).

Arguments to the trigger method can be identified using parameter references with successive indices, \$1, \$2 etc. The declaration of engine specifies its type as being CoordinatorEngine though this is not strictly necessary since it can be inferred from the type of \$0.

Similarly, variables recovered and identifier are bound by evaluating the expressions on the right of the = operator. Note that the binding for engine has been established before these variables are bound so it can be referenced in the evaluated expression. Once again, type specifications are provided but they could be inferred.

The special syntax BIND NOTHING is available for cases where the rule does not need to employ any bindings. Alternatively, the BIND clause may be omitted.

Rule Expressions

Expressions which occur on the right hand side of the = operator in event bindings can be simple expressions i.e.

- references to previously bound variables
- references to the trigger method recipient or parameters
- references to the local variables in scope at the trigger point
- references to trigger method special variables \$!, \$^, \$#, \$* and \$@
- static field references
- primitive literals
- field accesses
- static or instance method invocations
- built-in operation invocations

n.b. built-in operations are explained in more detail below.

Expressions can also be complex expressions composed from other expressions using the usual Java operators: +, -, *, /, %, &, |, ^, &&, ||, !, =, ==, !=, <, <=, >, >=, new, etc. The ternary conditional expression operator, ? :, can also be employed. The type checker does its best to identify the types of simple and complex expressions wherever possible. So, for example, if it knows the type of bound variable `engine` then it will be able to employ reflection to infer the type of a field access `engine.recovered`, a method invocation `engine.isRecovered()`, etc.

Note:

- throw and return operations are only allowed as the last action in a sequence of rule actions (see below).
- Expressions should obey the normal rules regarding associativity and precedence.
- The trigger method recipient and parameters may be referred to by index using the symbols \$0 (invalid for a static method), \$1 etc. If the method has been compiled with the relevant debug options then symbolic references may also be used. So, for example, \$this may be used as an alias for \$0 and \$myArg may be used as an alias for \$1 if the method first parameter is declared with name myArg,
- If the trigger method has been compiled with the relevant debug options then local variables may be referenced symbolically using the same syntax to method parameters. So, for example, if variable idx is in scope at the trigger point then \$idx can be used to obtain its value.
- Special variables provide access to other trigger method data. There are currently 5 such special variables:
 - \$! is valid in at AT EXIT rule and is bound to the return value on the stack at the point where the rule is triggered. Its type is the same as the trigger method return type. The rule will fail to inject if the trigger method return type is void.
 - \$! is also valid in an AFTER INVOKE rule and is bound to the return value on the stack at the point where the rule is triggered. Its type is the same as the invoked method return type. The rule will fail to inject if the invoked method return type is void.
 - \$^ is only valid in an AT THROW rule and is bound to the throwable on the stack at the point where the rule is triggered. Its type is Throwable.
 - \$# has type int and identifies the number of parameters supplied to the trigger method.
 - \$* is bound to an Object[] array containing the trigger method recipient, \$this, in slot 0 and the trigger method parameter values, \$1, \$2 etc in slots 1, 2 etc (for a static trigger method the value in slot 0 is null).
 - \$@ is only valid in an AT INVOKE rule and is bound to an Object[] array containing the AT INVOKE target method recipient in slot 0 and the call arguments for the target method installed in slots 1 upwards *in call order* (if the target method is static the value in slot 0 is null). Note that this variable is not valid in AFTER INVOKE rules. The array contains the call arguments located on the stack just before the trigger method calls the AT INVOKE target method. These values are no longer available after the call has completed.
- Assignments may update the bindings for rule variables introduced in the BINDS clause, parameter or local variables, instance fields, static fields or the return value

special variables \$!. Assignments are not currently allowed to update any of the other special variables.

- Assignments to parameter variables or local variables are *visible* on resumption of the trigger method. For example, assume that a rule includes an assignment such as \$name = "Ernie", where name is either a parameter variable or a local variable in scope at the trigger point. If name has value "Bert" when the rule is triggered and the assignment actually gets executed then on resumption of the trigger method name will have value "Ernie". Note that assignments cannot be made to \$this (or, equivalently, \$0) as the recipient argument for an instance method is always final.
- Assignment to \$! updates the return value on top of the stack at the trigger point, causing the trigger method to return this updated value. The same effect can be achieved by executing a RETURN expression.
- Byteman provides the English language keywords listed below which can be used in place of the related standard Java operators (in brackets):
OR (||), AND (&&), NOT (!), LE (<=), LT (<), EQ (==), NE (!=), GE (>=), GT (>),
TIMES (*), DIVIDE (/), PLUS (+), MINUS (-), MOD (%),
keywords are recognised in either upper or lower (but not mixed) case
keywords may clash with the same names where they occur as legal Java identifiers in the target classes and methods specified in Byteman rules

Rule Conditions

Rule conditions are nothing more than rule expressions with boolean type. For example,

```
# condition example
RULE countdown at commit
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
AT READ state
BIND engine:CoordinatorEngine = $this;
    recovered:boolean = engine.isRecovered();
    identifier:String = engine.getId()
IF    recovered
    . . .
ENDRULE
```

merely tests the value of bound variable recovered. The same effect could be achieved by using the following condition

```
# condition example 2
RULE countdown at commit
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
AT READ state
BIND engine:CoordinatorEngine = $this,
    . . .
IF    engine.isRecovered()
    . . .
ENDRULE
```

Alternatively, if, say, the instance employed a public field, recovered, to store the boolean value returned by method isRecovered then the same effect would be achieved

by the following condition.

```
# condition example 3
RULE countdown at commit
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
AT READ state
BIND engine:CoordinatorEngine = $this,

    . . .
IF    engine.recovered
    . . .
ENDRULE
```

Note that the boolean literal `true` is available for use in expressions so a rule which should always fire can use this as the condition expression.

Rule Actions

Rule actions are either a rule expression or a return or throw action or a sequence of rule expressions separated by semi-colons, possibly ending with a return or throw action. Rule expressions occurring in an action list may have arbitrary type, including void type.

A return action is the `return` keyword possibly followed by a rule expression which is used to compute a return value. A return action causes a return from the triggering method so it may omit a return value if and only if the method is void. If a return value is employed then the type checker will ensure that its type is assignable to the return type of the trigger method. So, for example, the following use of `return` is legitimate assuming method `commit` has return type `boolean`:

```
# return example
RULE countdown at commit
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
AT READ state
    . . .
DO debug("returning early with failure");
   return false
ENDRULE
```

A throw action is the `throw` keyword followed by an throwable constructor expression. An throwable constructor expression is the keyword `new` followed by the class name of the throwable which is to be thrown followed by an argument list. The argument list may be empty i.e. it may consist of an open and close bracket pair. Alternatively, the brackets may include a single rule expression or a sequence of rule expressions separated by commas. If no arguments are supplied the throwable type must implement an empty constructor. If arguments are supplied then the throwable type must implement a constructor whose signature is type-compatible. n.b. for hysterical reasons the `new` keyword may be omitted from the throwable constructor expression which follows the `throw` keyword.

A throw action causes a throwable of the type named in the exception constructor to be created and thrown from the *triggering* method. In order for this to be valid the expression type must either be assignable to `java.lang.RuntimeException` or `java.lang.Error` or be explicitly declared in the triggering method's throws list. The type checker will throw a type exception if either of these conditions is not met. So, for example, the following use of `throw` is legitimate assuming method `commit` includes `WrongStateException` in its throws list.

```
# throw example
RULE countdown at commit
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
AT READ state
    . . .
DO debug("throwing wrong state");
    throw new WrongStateException()
ENDRULE
```

An empty action list may be specified using the keyword NOTHING.

Built-In Calls

Built-in calls are written without a recipient as though they were invocations of a method on `this`. The rule engine identifies calls in this format and translates them to runtime invocations of helper class instance methods. So, referring back to the last few examples, it is apparent that the helper class implements a debugging method with signature

```
boolean debug(String message)
```

This method prints the supplied string to `System.out` and always returns `true`. It can be used in a rule action to display a trace message, for example:

```
DO debug("killing JVM"), killJVM()
```

When the `debug` built-in is executed the rule engine calls the corresponding method of the current helper instance passing it the string `"killing JVM"`. Method `killJVM` is another built-in implemented by an instance method of the default helper class `Helper`.

Note that method `debug` has a boolean signature so that tracing can also be performed in rule conditions. This would normally occur in combination with a test of some bound variable or method parameter, for example:

```
IF debug("checking for recovered participant")
    AND
    participant.isRecovered()
    AND
    debug("recovered participant " + participant.getId())
```

n.b. `AND` is an alternative token for the Java `&&` operator.

The rule language implementation automatically exposes all public instance methods of class `Helper` as built-in operations. So when the rule type checker encounters an invocation of `debug` with no recipient supplied it identifies that `debug` is a method of class `Helper` and automatically type checks the call against this method. At execution time the call is executed by invoking the implementation of `debug` on the helper instance created under the rule trigger call.

This feature allows additional built-ins to be added to the rule engine simply by adding new helper implementations. No changes are required to the parser, type checker and compiler in order for this to work.

User-Defined Rule Helpers

A rule can specify its own helper class if it wants to extend, override or replace the set of built-in calls available for use in its event, condition or action. For example, in the following rule, class `FailureTester` is used as the helper class. Its boolean instance method `doWrongState(CoordinatorEngine)` is called from the condition to decide whether or

not to throw a `WrongStateException`.

```
# helper example
RULE help yourself
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
HELPER com.arjuna.wst11.messaging.engines.FailureTester
AT EXIT
IF doWrongState($0)
DO throw new WrongStateException()
ENDRULE
```

A helper class does not need to implement any special interface or inherit from any pre-defined class. It merely needs to provide instance methods to resolve the built-in calls which occur in the rule. By sub-classing the default helper it is possible to extend or override the default set of methods. For example, the following rule employs a helper which adds emphasis to the debug messages printed by the rule.

```
# helper example 2
RULE help yourself but rely on others
CLASS com.arjuna.wst11.messaging.engines.CoordinatorEngine
METHOD commit
HELPER HelperSub
AT ENTRY
IF NOT flagged($this)
DO debug("throwing wrong state");
   flag($this);
   throw new WrongStateException()
ENDRULE
```

```
class HelperSub extends Helper
{
    public boolean debug(String message)
    {
        super("!!! IMPORTANT EVENT !!! " + message);
    }
}
```

The rule is still able to employ the built-in methods `flag` and `flagged` defined by the default helper class.

The examples above use a `HELPER` line in the rule body to reset the helper for a specific rule. It is also possible to reset the helper for all subsequent rules in a file by adding a `HELPER` line outside of the scope of a rule. So, in the following example the first two rules use class `HelperSub` while the third one uses class `YellowSub`.

```
HELPER HelperSub
# helper example 3
RULE helping hand
. . .
RULE I can't help myself
. . .
RULE help, I need somebody
CLASS . . .
METHOD . . .
HELPER YellowSub
```


The Rule Helper Lifecycle Methods

It is occasionally useful to be able to perform some sort of setup activity when rules are loaded or a teardown activity when rules are unloaded. For example, if tracing rules are loaded to collect statistics on program execution it would be convenient to add a background thread which wakes up at regular intervals in order to print and then zero the value of the various counters incremented by the rules. Similarly, it would be helpful to be able to detect that all the tracing rules had been unloaded so that the thread can be shutdown, avoiding wasted CPU time. The rule engine supports a lifecycle model for loading and unloading which makes this sort of setup and teardown simple to achieve.

There are four lifecycle events in the model: activate, install, uninstall and deactivate. Although these lifecycle events are associated with loading and unloading of rules, the focus of the event is the helper class associated with the rule being loaded/unloaded. It is the helper class which provides a callback method to handle the lifecycle event. The four lifecycle events are generated according to the following model.

Assume that we have a helper class H and a set of *installed* rules $R(H)$ employing H as their helper. Obviously $R(H)$ is empty at bootstrap. When a rule $r(H)$ with helper H has been loaded (either during agent bootstrap or via the dynamic listener), injected and typechecked it is *installed* into the set $R(H)$. When an installed rule is unloaded via the dynamic listener it is *uninstalled* from the set $R(H)$.

- an activate event occurs when an install cause $R(H)$ to transition from empty to non-empty
- an install event occurs when $r(H)$ is installed in $R(H)$
- an uninstall event occurs when $r(H)$ is uninstalled from $R(H)$
- a deactivate event occurs an uninstall causes $R(H)$ to transition from non-empty to empty

Note that an install always generates an activate event before the associated install event. An uninstall always generates an uninstall event before any associated deactivate event.

The helper class H is notified of these events if it implements any of the corresponding static methods:

```
public static void activated()  
public static void installed(Rule rule)  
public static void installed(String ruleName)  
public static void uninstalled(Rule rule)  
public static void uninstalled(String ruleName)  
public static void deactivated()
```

`activated()` is called when an activate event occurs. It can perform a one-off set up operation on behalf of all rules employing the helper.

`deactivated()` is called when a deactivate event occurs. It can perform a one-off tear down operation on behalf of all rules employing the helper.

`installed(Rule)` is called when an install event occurs. It can perform a set up operation specific to the supplied rule.

`deinstalled(Rule)` is called when an install event occurs. It can perform a tear down operation specific to the supplied rule.

`installed(String)` and `uninstalled(String)` can also be implemented as alternatives to `installed(Rule)` and `uninstalled(Rule)` if the helper can

make do with the rule name rather than using the `ByteMan RuLe` instance. Note that if both flavours are implemented only the method which takes a `Rule` will be called.

It is important to understand that loading and unloading of a rule does not always initiate lifecycle processing. If a rule does not parse or typecheck correctly it will not be installed so it will not generate activate or install events. If later this rule is unloaded it will not generate uninstall or deactivate events since it was never installed. It is also possible for a valid rule to be loaded and unloaded without initiating lifecycle processing. For example, the rule may never get injected because no matching trigger class has been loaded into the JVM.

Byteman Rule Language Standard Built-Ins

The default helper class provides the following standard suite of built-in calls for use in rule expressions. These are primarily intended for use in condition and action expressions but they may also be called in event bindings. They provide features which are designed to make it easy to perform complex tests, in particular to coordinate the actions of threads in multi-threaded applications. Built-in operations divide into three categories, thread coordination operations, rule state management operations and trace and debug operations

Thread Coordination Operations

Waiters

The rule engine provides Waiters used to suspend threads during rule execution and then have other threads wake them up. The wakeup can simply allow the suspended thread to resume execution of the rule which suspended it. Alternatively, it can force the waiting thread to exit from the triggering method with an exception. The API defined by the helper class is

```
public void waitFor(Object identifier)
public void waitFor(Object identifier, long millisecsWait)
public boolean waiting(Object identifier)
public boolean signalWake(Object identifier)
public boolean signalWake(Object identifier, boolean
mustMeet)
public boolean signalThrow(Object identifier)
public boolean signalThrow(Object identifier, boolean
mustMeet)
```

As with CountDowns, Waiters are identified by an arbitrary object. Note that the wait operation is not performed by invoking `Object.wait` on `identifier`. Doing so might interfere with locking and synchronization operations performed by the triggering method or its callers. The identifier is merely used by the rule engine to associate wait and signal operations. The Helper class employs it's own private Waiter object to manage the synchronization activity.

`waitFor` is intended for use in a rule action. It suspends the current thread on the Waiter associated with the identifier until either a `signalWake` or a `signalThrow` is called with the same identifier. In the former case the thread will continue processing any subsequent actions and then return from the trigger call. In the latter case the thread will throw a runtime exception from the triggering method call frame. The version without a wait parameter will never time out. The version which employs a wait parameter will time out after the specified number of milliseconds.

`waiting` is intended for use in rule conditions. it will return true if any threads are waiting on the relevant Waiter for a signal. It returns false if there are no threads waiting.

`signalWake` is intended for use in rule conditions or actions. If there are threads waiting on the Waiter associated with `identifier` it wakes them and returns true. If not it returns false. Note this behaviour ensures that a race between multiple threads to signal waiting threads from a rule condition can only have one winner.

`signalWake` takes an optional argument `mustMeet` which is useful in situations where it

cannot be guaranteed that the waiting thread will reach its trigger point before the signalling thread arrives at its trigger point. If this argument is supplied as `true` then the signalling thread will not deliver its signal until another thread is waiting. If necessary the signalling thread will suspend until a waiting thread arrives. Supplying value `false` is equivalent to omitting the optional argument.

`signalThrow` is identical to `signalWake` except that it does not just wake any waiting threads. It also causes them to throw a runtime exception of type `ExecuteException` from their triggering method call frame when they wake up.

`signalThrow` also takes an optional argument `mustMeet` which enables the same behaviour as for `signalWake`.

Rendezvous

Waiters are useful in situations where there is an asymmetrical relationship between threads: one or more threads need to wait for an event which will be signalled by the thread in which the event happens. A rendezvous provides a way of synchronizing where there is no such asymmetry. A rendezvous also provides a way of introducing asymmetry since it sorts threads by order of arrival. The value returned from the rendezvous built-in can be checked to identify, say, the first (or last) thread to arrive and that thread can be the one whose action is triggered.

```
public boolean createRendezvous(Object identifier,
                                int expected)
public boolean createRendezvous(Object identifier,
                                int expected,
                                boolean rejoinable)
public boolean rendezvous(Object identifier)
public boolean isRendezvous(Object identifier, int expected)
public int getRendezvous(Object identifier, int expected)
public int deleteRendezvous(Object identifier, int expected)
```

`createRendezvous` creates a rendezvous identified by `identifier`. `count` identifies the number of threads which must meet at the rendezvous before any one of them is allowed to continue execution. The optional argument `rejoinable` defaults to `false` in which case any attempt to meet once the first count threads have arrived will fail. If it is supplied as `true` then once count threads have arrived the rendezvous will be reset, enabling another round of meetings to occur. `createRendezvous` returns `true` if the rendezvous is created. If a rendezvous identified by `identifier` already exists it returns `false`. Note that it is legitimate (although pathological) to supply a count of 1.

`rendezvous` is called to meet other threads at a rendezvous identified by `identifier`. If the number of threads (*including the calling thread*) arrived at the rendezvous is less than the expected count then the calling thread is suspended. If the number of threads equals the expected count then all suspended threads are awoken. A rejoinable rendezvous has its arrived count reset to 0 at this point. If the rendezvous is not rejoinable then it is deleted and any subsequent call to `rendezvous` using the original identifier will return -1.

`isRendezvous` will return `true` if a rendezvous identified by `identifier` with the expected count is currently active. If there is no active rendezvous identified by `identifier` or it exists but has a different expected count then `getRendezvous` will return `false`.

`getRendezvous` will return the number of threads waiting at the rendezvous identified by

`identifier` or 0 if no threads are currently waiting. If there is no rendezvous identified by `identifier` or it exists but has a different expected count then `getRendezvous` will return -1.

`deleteRendezvous` deletes a rendezvous, breaking the association between `identifier` and the rendezvous and forcing any threads waiting under a call to `rendezvous` to return immediately with result -1. If a rendezvous with the correct expected count is found and successfully deleted it returns true. If there is no such rendezvous or if it is deleted either by another concurrent call to `deleteRendezvous()` or because a concurrent call to `rendezvous()` completes the rendezvous it returns false.

Joiners

Joiners are useful in situations where it is necessary to ensure that a thread does not proceed until one or more related threads have exited. This is not always a requirement for an application to execute correctly but may be necessary to validate a test scenario. For example, a socket listener thread may create connection manager threads to handle incoming connection requests. The listener might use the connection object to notify connection manager threads of a forced exit. It does not necessarily have to retain a handle on the connection thread and explicitly call `Thread.join()` to be sure the thread will exit when notified. However, a test may want to check the thread pool to be sure all activity has completed. This means the test needs to be able to accumulate a list of managed threads and then subsequently join them either from the manager thread or from a test thread.

```
public boolean createJoin(Object identifier, int expected)
public boolean isJoin(Object identifier, int expected)
public boolean joinEnlist(Object identifier, int expected)
public boolean joinWait(Object identifier, int expected)
```

`createJoin` creates a Joiner which can subsequently be referenced by `identifier`. `expected` identifies the number of threads which are to be joined. If a Joiner is created it returns true. If a Joiner is currently identified by `identifier` it returns false.

`isJoin` tests whether `identifier` identifies a Joiner with the given expected count. If a Joiner with the given expected count is currently identified by `identifier` it returns true otherwise it returns false

`joinEnlist` adds the calling thread to the list of threads associated with a Joiner and returns true, allowing the thread to proceed towards exit. If `identifier` does not identify a Joiner or identifies a Joiner with the wrong expected count it returns false. It also returns false if the calling thread is already contained in the Joiner's thread list or if the number of threads added to the list has reached the expected count.

`JoinWait` suspends the calling thread until the number of threads in the list associated with the Joiner reaches the expected count. It then joins each thread in the list and returns true. If `identifier` does not identify a Joiner or identifies a Joiner with the wrong expected count it returns false.

Aborting Execution

The rule engine provides two built-ins for use in rule actions which allow execution of the triggering method to be aborted. The API defined by the helper class is

```

public void killThread()
public void killJVM()
public void killJVM(int exitCode)

```

`killThread` causes a runtime exception of type `ExecuteException` to be thrown from the triggering method call frame. This will effectively kill the thread unless a catch-all exception handler is installed somewhere up the call stack.

`killJVM` results in a call to `java.lang.Runtime.getRuntime().halt()`. This effectively kills the JVM without any opportunity for any registered exit handlers to run, simulating a JVM crash. If `exitCode` is not supplied it is defaulted to -1

Rule State Management Operations

CountDowns

The rule engine provides `CountDowns` which can be used to ensure that firing of some given rule will only occur after other rules have been triggered or fired a certain number of times. The API defined by the helper class is

```

public boolean createCountDown(Object identifier, int count)
public boolean getCountDown(Object identifier)
public boolean countDown(Object identifier)

```

`CountDowns` are identified by an arbitrary object, allowing successive calls to the `countDown` API to apply to the same or different cases. This identification can be made across different rule and helper instances. For example, one rule might include action `createCountDown($0, 1)` and another rule might include condition `countDown($0)`. A `CountDown` created by the first rule would only be decremented if the second rule was triggered from a method call with the same value for `this`. `CountDowns` created by invocations with distinct values for `this` would match up accordingly. However, if the `CountDown` was identified using a common `String` literal (i.e. action and condition were `createCountDown("counter", 1)` and `countDown("counter")`, respectively), then the `CountDown` created by the first rule would be decremented by the next firing of the second rule irrespective of whether the trigger method calls were on related instances.

`createCountDown` is used to create a `CountDown`. `count` specifies how many times the `CountDown` will be decremented before a decrement operation fails i.e. if `count` is 1 then the `CountDown` will decrement once and then fail at the next decrement. If `count` is supplied with a value less than 1 it will be replaced with value 1. `createCountDown` would normally be employed in a rule action. However, it is defined to return `true` if a new `CountDown` is created and `false` if there is already a `CountDown` associated with the identifier. This allows it to be used in rule conditions where several rules may be racing to create a `CountDown`.

`getCountDown` is for use in a rule condition to test whether a `CountDown` associated with a given identifier is present, returning `true` if so otherwise `false`.

`countDown` is for use in a rule condition to decrement a `CountDown`. It returns `false` if the decrement succeeds or if there is no `CountDown` associated with identifier. It returns `true` if the `CountDown` fails i.e. it has `count 0`. In the latter case the association between the identifier and the `CountDown` is removed, allowing a new `CountDown` to be started using the same identifier. Note that this behaviour ensures that a race between multiple threads to decrement a counter from one or more rule conditions can only have one winner.

Flags

The rule engine provides a simple mechanism for setting, testing and clearing global flags. The API defined by the helper class is

```
public boolean flag(Object identifier)
public boolean flagged(Object identifier)
public boolean clear(Object identifier)
```

As before, Flags are identified by an arbitrary object. All three methods are designed to be used either in conditions or actions.

`flag` can be called to ensure that the Flag identified by `identifier` is set. It returns `true` if the Flag was previously clear otherwise `false`. Note that the API is designed to ensure that race conditions between multiple threads trying to set a Flag from rule conditions can only have one winner.

`flagged` tests whether the Flag identified by `identifier` is set. It returns `true` if the Flag is set otherwise `false`.

`clear` can be called to ensure that the Flag identified by `identifier` is clear. It returns `true` if the Flag was previously set otherwise `false`. Note that the API is designed to ensure that race conditions between multiple threads trying to clear a Flag from rule conditions can only have one winner.

Counters

The rule engine provides Counters which maintain global counts across independent rule triggerings. They can be created and initialised, read, incremented and decremented in order track and respond to the number of times various triggerings or firings have happened. Note that unlike `CountDowns` there are no special semantics associated with decrementing a Counter to zero. They may even have negative values. The API defined by the helper class is

```
public boolean createCounter(Object o)
public boolean createCounter(Object o, int count)
public boolean deleteCounter(Object o)
public int incrementCounter(Object o, int amount)
public int incrementCounter(Object o)
public int decrementCounter(Object o)
public int readCounter(Object o)
public int readCounter(Object o, boolean zero)
```

As before, Counters are identified by an arbitrary object. All methods are designed to be used in rule conditions or actions.

`createCounter` can be called to create a new Counter associated with `o`. If argument `count` is not supplied then the value of the new Counter defaults to 0. `createCounter` returns `true` if a new Counter was created and `false` if a Counter associated with `o` already exists. Note that the API is designed to ensure that race conditions between multiple threads trying to create a Counter from rule conditions can only have one winner.

`deleteCounter` can be called to delete any existing Counter associated with `o`. It returns `true` if the Counter was deleted and `false` if no Counter was associated with `o`. Note that the API is designed to ensure that race conditions between multiple threads trying to delete a Counter from rule conditions can only have one winner.

`incrementCounter` can be called to increment the Counter associated with `o`. If no such

Counter exists it will create one with value 0 before incrementing it. `incrementCounter` returns the new value of the Counter. If `amount` is omitted it defaults to 1.

`decrementCounter` is equivalent to calling `incrementCounter(o, -1)` i.e. it adds -1 to the value of the counter.

`readCounter` can be called to read the value of the Counter associated with `o`. If no such Counter exists it will create one with value 0. If the optional flag argument `zero` is passed as `true` the counter is atomically read and zeroed. `zero` defaults to `false`.

Timers

The rule engine provides Timers which allow measurement of elapsed time between triggerings. Timers can be created, read, reset and deleted via the following API

```
public boolean createTimer(Object o)
public long getElapsedTimeFromTimer(Object o)
public long resetTimer(Object o)
public boolean deleteTimer(Object o)
```

As before, Timers are identified by an arbitrary object. All methods are designed to be used in rule conditions or actions.

`createTimer` can be called to create a new Timer associated with `o`. `createTimer` returns `true` if a new Timer was created and `false` if a Timer associated with `o` already exists.

`getElapsedTimeFromTimer` can be called to obtain the number of elapsed milliseconds since the Timer associated with `o` was created or since the last call to `resetTimer`. If no timer associated with `o` exists a new timer is created before returning the elapsed time.

`resetTimer` can be called to zero the Timer associated with `o`. It returns the number of seconds since the Timer was created or since the last previous call to `resetTimer`. If no timer associated with `o` exists a new timer is created before returning the elapsed time.

`deleteTimer` can be called to delete the Timer associated with `o`. `deleteTimer` returns `true` if a new Timer was deleted and `false` if no Timer associated with `o` exists.

Recursive Triggering

When a rule is triggered it executes the Java code in the event, condition and action and this may include calls to Helper methods or methods defined by the application under test or by the JVM runtime. If any of these methods match Byteman rules then this may result in a recursive entry to the rule execution engine. In some cases this may be desirable. However, in other cases this recursive entry may cause an infinite triggering chain and it is necessary to disable triggering while the rule executes. For example, the following rule will fail because of this problem:

```
RULE infinite triggering chain
CLASS java.io.FileOutputStream
METHOD open(String, int)
AT EXIT
BIND filename = $1
IF TRUE
DO traceLn("openlog", "Opened " + $1 + " for write")
ENDRULE
```


The problem is that on the first call to builtin method `traceIn(Object, String)` the default helper class attempts to open a trace file which it will then associate with key "openlog". In doing so it calls `FileOutputStream.open` and retriggers the rule.

One way round this is to specify a condition which will break the chain. The trace file will have a name of the form "traceNNN.txt" so the following version of the rule works as desired:

```
RULE infinite triggering chain broken using IF test
CLASS java.io.FileOutputStream
METHOD open(String, int)
AT EXIT
BIND filename = $1
IF !filename.matches("trace.*")
DO traceIn("openlog", "Opened " + $1 + " for write")
ENDRULE
```

With this version the rule is triggered recursively under the call to `traceIn` but the condition stops it being fired, breaking the recursion.

Of course in other cases it may not be so simple to come up with a condition which avoids recursive firing. So, the default helper provides the following method which allows triggering to be disabled or re-enabled while the rule is executing

```
public void setTriggering(boolean enabled)
```

If `enabled` is false then triggering is disabled during execution of subsequent expressions in the rule body. If it is true then triggering is re-enabled.

This can be used to implement the behaviour shown in the example above without the need to identify a suitable conditional

```
RULE infinite triggering chain broken using IF test
CLASS java.io.FileOutputStream
METHOD open(String, int)
AT EXIT
BIND filename = $1
IF TRUE
DO setTriggering(false);
   traceIn("openlog", "Opened " + $1 + " for write")
ENDRULE
```

Note that once execution of the rule has completed triggering is automatically re-enabled so, in this case, there is no need to call `setTriggering(true)` at the end of the DO clause.

Trace and Debug Operations

Debugging

The rule engine provides a simple built-in debug method to support conditional display of messages during rule execution. The API defined by the helper class is

```
public boolean debug(String message)
```

`debug` prints the supplied message to `System.out`, prefixed with the name of the rule being executed. It always returns true, allowing debug messages to be used in conditions by ANDing them with other boolean expressions.

Generation of debug messages can be switched on by setting the following system property on the JVM command line:

```
org.jboss.byteman.debug
```

Tracing

The rule engine provides a set of built-in methods to support logging of trace messages during execution. Messages may be logged to `System.out`, `System.err` or to a named file. The API defined by the helper class is

```
public boolean traceOpen(Object identifier, String filename)
public boolean traceOpen(Object identifier)
public boolean traceClose(Object identifier)
public boolean trace(Object identifier, String message)
public boolean traceLn(Object identifier, String message)
public boolean trace(String message)
public boolean traceLn(String message)
```

`traceOpen` opens the file identified by `fileName` and associates it with `identifier`, returning `true`. `filename` can be either a relative or absolute path. Relative file names are located relative to the current working directory of the JVM. If there is already a file associated with `identifier` then `traceOpen` immediately returns `false`. If a file with the given name already exists it is opened in append mode. If `filename` is omitted then a unique name is generated for the file which is guaranteed not to match any existing trace file in the current working directory.

`traceClose` closes the file associated with `identifier` and removes the association, returning `true`. If no open file is associated with `identifier` it returns `false`.

`trace` prints `message` to file associated with `identifier`, returning `true`. If no open file is associated with `identifier` then a file will be opened and associated with `identifier` as if a call to `trace` had been made with no file name supplied. If `identifier` is omitted then the output is written to `System.out`.

`traceLn` prints `message` to file associated with `identifier` and appends a newline to the file, returning `true`. If no open file is associated with `identifier` then a file will be opened and associated with `identifier` as if a call to `trace` had been made with no file name supplied. If `identifier` is omitted then the output is written to `System.out`.

A caveat applies to the above descriptions for three special cases. If `identifier` is `null` or the string `"out"`, then `trace` and `traceLn` write to `System.out`. If `identifier` is the string `"err"`, then `trace` and `traceLn` write to `System.err`. `traceOpen` and `traceClose` always return `false` immediately if `identifier` has any of these values. Calls to `trace(message)` and `traceLn(message)` which omit `identifier` are implemented by calling, respectively, `trace("out", message)` and `traceLn("out", message)`.

Stack Management Operations

Checking The Call Tree

The rule engine provides a set built-in methods which can be used to check the caller stack at the point where the rule was triggered. Obviously, the rule will only be triggered from a method which matches the name in its `METHOD` clause. However, sometimes it is useful to be able to know which method called the trigger rule. For example, the following

rule will only fire when method `MyClass.getData()` is called from method `handleIncoming` of class `MyOtherClass`:

```
RULE trace getData call under handleIncoming
CLASS MyClass
METHOD myGetData
IF callerEquals("MyOtherClass.handleIncoming", true)
DO traceStack("found the caller!\n", 10)
ENDRULE
```

The API defined by the helper class is

```
public boolean callerEquals(String name)
public boolean callerEquals(String name,
                             int frameCount)
public boolean callerEquals(String name,
                             int startFrame,
                             int frameCount)
public boolean callerEquals(String name,
                             boolean includeClass)
public boolean callerEquals(String name,
                             boolean includeClass,
                             int frameCount)
public boolean callerEquals(String name,
                             boolean includeClass,
                             int startFrame,
                             int frameCount)
public boolean callerEquals(String name,
                             boolean includeClass,
                             boolean includePackage)
public boolean callerEquals(String name,
                             boolean includeClass,
                             boolean includePackage,
                             int frameCount)
public boolean callerEquals(String name,
                             boolean includeClass,
                             boolean includePackage,
                             int startFrame,
                             int frameCount)
```

```

public boolean callerMatches(String regExp)
public boolean callerMatches(String regExp,
                             int frameCount)
public boolean callerMatches(String regExp,
                             int startFrame,
                             int frameCount)
public boolean callerMatches(String regExp,
                             boolean includeClass)
public boolean callerMatches(String regExp,
                             boolean includeClass,
                             int frameCount)
public boolean callerMatches(String regExp,
                             boolean includeClass,
                             int startFrame,
                             int frameCount)
public boolean callerMatches(String regExp,
                             boolean includeClass,
                             boolean includePackage)
public boolean callerMatches(String regExp,
                             boolean includeClass,
                             boolean includePackage,
                             int frameCount)
public boolean callerMatches(String regExp,
                             boolean includeClass,
                             int startFrame,
                             int frameCount)

public boolean callerCheck(String match, boolean isRegExp,
                           boolean includeClass,
                           boolean includePackage,
                           int startFrame,
                           int frameCount)

```

The real action happens in method `callerCheck(String, boolean, boolean, boolean, int, int)`. All the other methods call each other defaulting the various missing arguments until they bottom out in a call to this method.

`callerCheck` tests `frameCount` call frames starting from `startFrame` and returns true if any of them matches `match`.

`startFrame` defaults to 1 which identifies the stack frame for the caller of the trigger method (0 can be used to identify the trigger method itself). `framecount` also defaults to 1 which means that when `startFrame` and `frameCount` are defaulted the call only checks the frame for the caller of the trigger method.

`includeClass` and `includePackage` default to false. If `includeClass` is false then `match` is compared against the bare name of the method associated with each selected stack frame. If `includeClass` is true and `includePackage` is false then `match` is compared to the class qualified method name. If both are true then `match` is compared against the full package and class qualified method name.

If `isRegExp` is true then `match` is compared as a regular expression compared using `String.matches()` otherwise it compared using `String.equals()`. The `callerEquals`

methods pass this argument to `callerCheck` as `false` and the `callerMatches` methods pass this argument as `true`.

Tracing the Caller Stack

The rule engine provides a set built-in methods which can be used to obtain a string representation of a stack trace or to print a stack trace to a trace file. The API defined by the helper class is

```
public void traceStack()  
public void traceStack(String prefix)  
public void traceStack(String prefix, Object key)  
public void traceStack(int maxFrames)  
public void traceStack(String prefix, int maxFrames)  
public void traceStack(String prefix,  
                        Object key,  
                        int maxFrames)  
  
public String formatStack()  
public String formatStack(String prefix)  
public String formatStack(int maxFrames)  
public String formatStack(String prefix, int maxFrames)
```

The real action happens in methods `traceStack(String, Object, int)` and `formatStack(String, int)`. All the other methods call each other defaulting the various missing arguments until they bottom out in a call to one of these two methods.

`formatStack(String prefix, int maxFrames)` constructs a printable String representation of the stack starting from the trigger frame, including the fully qualified method name, file and line number for each frame followed by a new line.

If `prefix` is non-null it prepended to the generated text. It defaults to `null` resulting in the prefix `"Stack trace for thread <current>\n"` being used as the prefix where `<current>` is substituted with the value of `Thread.currentThread().getName()`.

If `maxFrames` is positive and less than the number of frames in the stack then it is used to limit the number of frames printed and the text `"...\n"` is appended to the returned value otherwise all frames in the stack are included. `maxFrames` defaults to 0.

`traceStack(String prefix, Object key, int maxFrames)` constructs a stack trace by calling `formatStack(key, maxFrames)`. It then prints this to a trace file by calling `trace(key, <value>)`. As before, `prefix` defaults to `null` and `maxFrames` to 0. `key` defaults to `"out"` so this means that where it is omitted the trace printout will go to `System.out`.

Selective Stack Tracing Using a Regular Expression Filter

It is useful to be able to selectively filter a stack trace, limiting it, say, to include only frames from a given package or set of packages. The rule engine provides an alternative set of built-in methods which can be used to obtain or print a string representation of some subset of the stack filtered using a regular expression match. The API defined by the helper class is

```

public void traceStackMatching(String regExp)
public void traceStackMatching(String regExp, String prefix)
public void traceStackMatching(String regExp,
                               String prefix,
                               Object key)
public void traceStackMatching(String regExp,
                               boolean includeClass)
public void traceStackMatching(String regExp,
                               boolean includeClass,
                               String prefix)
public void traceStackMatching(String regExp,
                               boolean includeClass,
                               String prefix,
                               Object key)
public void traceStackMatching(String regExp,
                               boolean includeClass,
                               boolean includePackage)
public void traceStackMatching(String regExp,
                               boolean includeClass,
                               boolean includePackage,
                               String prefix)
public void traceStackMatching(String regExp,
                               boolean includeClass,
                               boolean includePackage,
                               String prefix,
                               Object key)

public void formatStackMatching(String regExp)
public void formatStackMatching(String regExp, String prefix)
public void formatStackMatching(String regExp,
                               boolean includeClass)
public void formatStackMatching(String regExp,
                               boolean includeClass,
                               String prefix)
public void formatStackMatching(String regExp,
                               boolean includeClass,
                               boolean includePackage)
public void formatStackMatching(String regExp,
                               boolean includeClass,
                               boolean includePackage,
                               String prefix)

```

Once again the action happens in the methods with the full set of parameters and the others merely call these methods defaulting the omitted arguments.

`formatStackMatching(String regExp, boolean includeClass, boolean includePackage, String prefix)` constructs a printable String representation of the stack prefixed by `prefix` as per `formatStack` with the difference that frames are only included if they match the regular expression `regExp`. `includeClass` and `includePackage` are defaulted and interpreted exactly as described in the `callerMatches` API. If `prefix` is null (the default) then the string "Stack trace for thread `<current>` matching `regExp`\n" is used as the prefix where `<current>` is substituted with the value of `Thread.currentThread().getName()` and `regExp` is substituted with the value of

regExp.

traceStackMatching(regExp, includeClass, includePackage, prefix, key) calls formatStackMatching to obtain a stack trace and then calls trace(String, Object) to print it to the trace stream identified by key. key defaults as described in the traceStack API listed above.

Stack Range Tracing

Another option for selective stack tracing is to specify a matching expression to select the start and end frame for the trace. The rule engine provides another set of built-in methods which can be used to obtain or print a string representation of a segment of the stack in this manner. The API defined by the helper class is

```
public void traceStackBetween(String from, String to)
public void traceStackBetween(String from, String to,
                               String prefix)
public void traceStackBetween(String from, String to,
                               String prefix, Object key)
public void traceStackBetween(String from, String to,
                               boolean includeClass)
public void traceStackBetween(String from, String to,
                               boolean includeClass,
                               String prefix)
public void traceStackBetween(String from, String to,
                               boolean includeClass,
                               String prefix, Object key)
public void traceStackBetween(String from, String to,
                               boolean includeClass,
                               boolean includePackage)
public void traceStackBetween(String from, String to,
                               boolean includeClass,
                               boolean includePackage,
                               String prefix)
public void traceStackBetween(String from, String to,
                               boolean includeClass,
                               boolean includePackage,
                               String prefix, Object key)
public void formatStackBetween(String from, String to)
public void formatStackBetween(String from, String to,
                               String prefix)
public void formatStackBetween(String from, String to,
                               boolean includeClass)
public void formatStackBetween(String from, String to,
                               boolean includeClass,
                               String prefix)
public void formatStackBetween(String from, String to,
                               boolean includeClass,
                               boolean includePackage)
public void formatStackBetween(String from, String to,
                               boolean includeClass,
                               boolean includePackage,
                               String prefix)
```

```

public void traceStackBetweenMatches(String from, String to)
public void traceStackBetweenMatches(String from, String to,
                                     String prefix)
public void traceStackBetweenMatches(String from, String to,
                                     String prefix,
                                     Object key)
public void traceStackBetweenMatches(String from, String to,
                                     boolean includeClass)
public void traceStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     String prefix)
public void traceStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     String prefix,
                                     Object key)
public void traceStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     boolean includePackage)
public void traceStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     boolean includePackage,
                                     String prefix)
public void traceStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     boolean includePackage,
                                     String prefix,
                                     Object key)
public void formatStackBetweenMatches(String from, String to)
public void formatStackBetweenMatches(String from, String to,
                                     String prefix)
public void formatStackBetweenMatches(String from, String to,
                                     boolean includeClass)
public void formatStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     String prefix)
public void formatStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     boolean includePackage)
public void formatStackBetweenMatches(String from, String to,
                                     boolean includeClass,
                                     boolean includePackage,
                                     String prefix)
public void traceStackRange(String from, String to,
                           boolean isRegExp,
                           boolean includeClass,
                           boolean includePackage,
                           String prefix, Object key)
public String formatStackRange(String from, String to,
                              boolean isRegExp,
                              boolean includeClass,
                              boolean includePackage,
                              String prefix)

```

Once again the action happens in the last two methods and all the other methods merely

provide a way of calling them with default values for various of the parameters. The `BetweenMatches` methods pass `true` for parameter `isRegExp` whereas the plain `Matches` methods pass `false`.

`formatStackRange` searches the stack starting from the trigger frame for a stack frame which matches `from`. If no match is found then `""` is returned. If `from` is `null` then the trigger frame is taken to be the start frame. It then searches the frames above the start frame for a frame which matches `to`. If no match is found or if `to` is `null` then all frames above the start frame are selected. Details of each frame in the matching range are appended to the supplied prefix to construct the return value. If `isRegExp` is `true` then the start and end frame are matched using `String.matches()` otherwise `String.equals()` is used. `includeClass` and `includePackage` are defaulted and interpreted as per method `formatStackMatching`. If `prefix` is `null` (the default) then the string `"Stack trace (restricted) for thread <current> \n"` is used as the prefix where `<current>` is substituted with the value of `Thread.currentThread().getName()`.

`traceStackRange` calls `formatStackRange` to obtain a trace of a stack range and then calls `trace(Object, String)` to print it to a trace file. `key` defaults to `"out"` as for the other stack trace APIs described above.

Tracing Named Thread Stacks

The default helper class also provides methods which can be used to trace or format the stack frames of a specific, named thread:

```
public void traceThreadStack(String threadName)
public void traceThreadStack(String threadName,
                             String prefix)
public void traceThreadStack(String threadName,
                             String prefix,
                             Object key)
public void traceThreadStack(String threadName,
                             int maxFrames)
public void traceThreadStack(String threadName,
                             String prefix,
                             int maxFrames)
public void traceThreadStack(String threadName,
                             String prefix,
                             Object key,
                             int maxFrames)
public void formatThreadStack(String threadName)
public void formatThreadStack(String threadName,
                             String prefix)
public void traceThreadStack(String threadName,
                             int maxFrames)
public void traceThreadStack(String threadName,
                             String prefix,
                             int maxFrames)
```

or to trace or format the stacks of all threads in the runtime:

```
public void traceAllStacks()
public void traceAllStacks(String prefix)
public void traceAllStacks(String prefix, Object key)
public void traceAllStacks(int maxFrames)
public void traceAllStacks(String prefix, int maxFrames)
public void traceAllStacks(String prefix, Object key, int maxFrames)
public void formatAllStacks()
public void formatAllStacks(String prefix)
public void formatAllStacks(int maxFrames)
public void formatAllStacks(String prefix , int maxFrames)
```

Default Helper Lifecycle Methods

The default helper provides an implementation of the four helper lifecycle methods which generate simple debug messages to `System.out`. So, with debug enabled you will see messages like the following as rules are loaded and then unloaded:

```
Default helper activated
Installed rule using default helper : my test rule
. . .
Installed rule using default helper : my second test rule
. . .
Uninstalled rule using default helper : my test rule
Uninstalled rule using default helper : my second test rule
Default helper deactivated
```

Using Byteman

Using Byteman from java or ant

If you are using Byteman from the java command line or from ant then you will need to download a Byteman release and install it locally. The latest Byteman release is available as a zip file from the Byteman project downloads page at

<http://www.jboss.org/byteman/downloads>

You need to download either the binary release or the full release and install it in a directory accessible on the machine on which you want to run Byteman. The rest of this document assumes that environment variable BYTEMAN_HOME identifies the directory into which the binary release is unzipped.

The binary release contains all the binary (classfile) jars and command scripts you will need to use Byteman, a copy of the programmers guide plus some sample scripts and an associated helper jar. The full release also provides source and javadoc jars.

Details of how to use Byteman from the command line are included in part 1 of the Byteman Tutorial [A Byteman Tutorial](#).

Details of how to configure an ant build script to employ the BUnit package which integrates Byteman with JUnit and TestNG are provided in part 2 of the Byteman Tutorial [Fault Injection Testing With Byteman](#).

The downloads page also contains a link to downloads for older binary release versions. Note that from Byteman 1.1 onwards the agent can only be run in JDK 6 or 7. Previous releases can also be run in JDK 5.

Using Byteman from maven

If you are using Byteman from maven, in particular, if you are using the BUnit package which integrates Byteman with JUnit and TestNG, then you normally only need to declare dependencies on the Byteman jars. You can download these jars from [JBoss public repository](#).

Details of how to configure your pom to provide the necessary jars are provided in part 2 of the Byteman Tutorial [Fault Injection Testing With Byteman](#).

Obtaining the source build tree

If you want to extend understand how Byteman works and, possibly, contribute to the Byteman project you will need to download the latest Byteman source tree. The sources are available from the master git repository at

<https://github.com/bytemanproject/byteman>

The source tree is structured as a maven project..

Building Byteman from the sources

Byteman can be built by executing command `mvn package` in the top level directory of the source tree. The build process should produce binary, osurec and javadoc jars in the target directory of each of the dependent submodules, `agent/target`, `submit/target`,

etc and assemble these into both a binary and a full release zip file in subdirectory download/target.

If you are using Byteman from ant or the java command line then you should unzip one of the download zip files into your local BYTEMAN_HOME directory as you would for any of the official downloads.

If you want to use Byteman from maven then you need to install the byteman jars in your local machine's maven repository by executing command `mvn install`. In this case before performing the install process you should modify the project version in the root pom and the parent version in each of the dependent submodule poms so that the version you install locally does not overwrite a version obtained from the JBoss master repository.

Running Applications with Byteman

The Byteman tutorials explain how to use Byteman to trace and test the behaviour of a variety of programs ranging from simple examples to sophisticated test cases. [The first tutorial](#) covers the basics of how to run Byteman. [The second tutorial](#) covers the use of Byteman for fault injection testing. It includes details of how to use the annotation based testing package BUnit which integrates Byteman with TestNG and JUnit. The tutorials are probably the best thing to look at if you are new to Byteman. The rest of this guide provides complete details of how to use Byteman from the Java command line and explains all the options which are available when using Byteman. Many of these options can also be configured when using Byteman from ant or maven.

Configuring a java agent

Using Byteman from the java command line is refreshingly simple. Installing Byteman at JVM startup requires only one extra argument. This argument points the JVM at the agent code in the byteman jar and at the script files containing your byteman rules. This is specified using the java command flag

```
-javaagent:agentlib=options
```

This is a standard option for JDK 1.6 and upwards.

agentlib is a path to the byteman jar. The build process inserts a metadata file in the jar which allows the JVM to identify the agent program entry point so everything else is shrink-wrapped.

options is a comma-separated sequence of options which are passed to the agent.

For example, setting

```
export JAVA_OPTS="-javaagent:$BYTEMAN_HOME/lib/byteman.jar=
script:$SCRIPT_HOME/HeuristicSaveAndRecover.btm,
script:$SCRIPT_HOME/JBossTSTrace.btm"
```

will cause the JVM to pick up the byteman jar file from the install root, BYTEMAN_HOME and inject all rules found in the two scripts `HeuristicSaveAndRecover.btm` and `JBossTSTrace.btm` located in directory `SCRIPT_HOME`. (n.b. the command should actually be all on one line without any line breaks – these have been inserted merely as an aid to readability)

Normally, the script option is all that is required. However there are several other options provided to configure more sophisticated features of the agent such as dynamic rule upload. The `bmjava` command script (see below) can be used to simplify the task of concatenating these options into a valid `-javaagent` argument.

Installing Byteman in a Running JVM using Script *bminstall*

If your Java application is already running you may still be able to install the Byteman agent into the JVM. The installed `bin` directory contains a script `bminstall`¹ which can be used to contact your application's JVM and install the agent. Once installed you can then use script `bmsubmit` described below to upload or unload rules via the Byteman agent listener. The command line syntax for the `bminstall` script is

```
bminstall [-p port] [-h host] [-b] \
          [-Dproperty[=value]]* pid
```

where terms between [] are optional * means zero or more repetitions and

pid is the process id of the JVM running your application or, alternatively, the name of the application as displayed by running command `jps -l`.

-h *host* means use *host* as the host name when opening the listener socket (the default is `localhost`)

-p *port* means use *port* as the port when opening the listener socket (the default is `9091`)

-b means add the byteman jar to the bootstrap class path

-D*property*=*value* means call `System.setProperty(property, value)` before starting the agent. More than one such property setting may be provided. If *value* is omitted then it defaults to `""`. Note that property must start with prefix `"org.jboss.byteman."`.

Note that when you identify the JVM using an application name instead of a process id you do not have to provide the full name but you must be sure the name is unambiguous. For example, if you want to install the agent into the JBoss Application Server you can use the full name `org.jboss.Main` or the abbreviated names `jboss.Main` or `Main`. Clearly, `Main` will often be a bad choice as many applications will use that name. The install will be done using the first matching JVM.

Note also that loading the agent at runtime may not work with certain JVMs. It will definitely not work unless your Java release includes a jar named `lib/tools.jar` below your top-level Java install directory and this jar must contain a class called `com.sun.tools.attach.VirtualMachine`. However, even with this jar in place the upload may fail.

Available -javaagent Options

Each option comprises a keyword prefix, identifying the type of the option, and a suffix, identifying the value of the option. Prefix and suffix are separated by a colon, `:`. Multiple options are separated by commas. Valid options include

script:scriptfile where *scriptfile* is a path to a file containing Byteman rules. This option causes the agent to read the rules in *scriptfile* and apply them to subsequently loaded classes. Multiple `script` arguments may be provided to ensure that more than one rule set is installed. It is possible to start the agent with no initial script arguments but this only makes sense if the listener option is supplied with value `true`.

listener:boolean where *boolean* is either `true` or `false`. This option causes the

¹ There is a Windows script called `bminstall.bat` which you can execute using the command `bminstall`. The Linux script is called `bminstall.sh` and you must supply this full name to execute it.

agent to start a listener thread at startup. The listener can be talked to using the `bmsubmit` script, either to provide listings of rule applications performed by the agent or to dynamically load, reload or unload rules. Loading or reloading of a rule causes any matching classes which have already been loaded into the JVM to be retransformed, inserting a trigger call for the newly loaded rules into their target methods. Unloading a rule causes trigger code to be removed from any matching classes.

port:portnum where *portnum* is a positive whole number. This option selects the port used by the agent listener when opening a server socket to listen on. If not supplied the port defaults to 9091. Supplying this option defaults the listener option to `true`.

address:host where *host* is a host name. This option selects the address used by the agent listener when opening a server socket to listen on. If not supplied the address defaults to 9091. Supplying this option defaults the listener option to `true`.

sys:jarfile where *jarfile* is a path to a jar file to be added to the JVM *system* class path. This option makes classes contained in the jar file available for use when type checking, compiling and executing rule conditions and actions. It provides a useful way to ensure that Helper classes mentioned in rules are able to be resolved. If a rule's trigger class is loaded by some other class loader this loader will normally have the system loader as a parent so references to the Helper class should resolve correctly.

boot:jarfile where *jarfile* is a path to a jar file to be added to the JVM *bootstrap* class path. This option provides a similar facility to the `sys` option but it ensures that the classes contained in the jar file are loaded by the bootstrap class loader. This is only significant when rules try to inject code into JVM classes which are loaded by the bootstrap class loader (which is a parent of the system loader).

prop:name=value where *name* identifies a System property to be set to *value* or to the empty String if no value is provided. Note that property names must begin with the prefix `"org.jboss.byteman."`.

Note that when injecting into JVM classes it is necessary to install the byteman jar into the boot classpath by passing option `boot:${BYTEMAN_HOME}/lib/byteman.jar`.

Without it compilation of the transformed class will fail because it cannot locate classes `Rule`, `ExecuteException`, `ThrowException` and `ReturnException`. Script `bmjava` automatically takes care of this requirement.

Running Byteman Using Script *bmjava*

The installed `bin` directory contains a script `bmjava` which can be used to assemble the options passed to the byteman agent and combine them with other java options supplied on the java command line. The command line syntax for this script is

```
bmjava [-p port] [-h host] \
  [-l script|-b jar|-s jar|-nb|-nl|-nj]* [--] javaargs
```

where terms between `[]` are optional, terms separated by `|` are alternatives, `*` means zero or more repetitions and

`-l script` means load the rules in file *script* during program start up

`-b jar` means add jar file *jar* to the bootstrap class path

`-s jar` means add jar file *jar* to the system class path

`-p port` means use *port* as the port when opening the listener socket (the default is 9091)

- h *host* means use *host* as the host name when opening the listener socket (the default is localhost)
- nb means don't add the byteman jar to the bootstrap class path (it is added by default)
- nl means don't start the agent listener (it is started by default)
- nj means don't inject into java.lang classes (this is allowed by default)

Submitting Rules Dynamically Using Script bmsubmit

The installed bin directory contains a script called `bmsubmit` which can be used to communicate with the agent listener started up when option `listener:true` is passed as an option to the Byteman agent (recall that this option is always enabled by the `bminstall` and `bmjava` scripts). This script can be used to upload rules into the running program, to unload previously loaded rules and to report which rules have been injected and/or whether any errors were detected when attempting injection. `bmsubmit` can also be used to install jars containing helper classes into the bootstrap or system classpath.

The command line syntax for the `bmsubmit` script is:

```
submit [-p port] [-h host] [-l|-u] [script1 . . . scriptN]
submit [-p port] [-h host] [-b|-s] jarfile1 . . .
submit [-p port] [-h host] -c
submit [-p port] [-h host] -y [prop1[=[value1]]. . .]
submit [-p port] [-h host] -v
```

Flags `-p` and `-h` can be used to supply the port and host address used to connect to the Byteman agent listener. If not supplied they default to 9091 and localhost, respectively.

Flag `-l` selects the default execution mode for `bmsubmit`. If no other flag is supplied this mode will be used. When run with no arguments `submit` lists all currently applied transformations. This listing includes details of failed transformations, typechecks and compiles.

When run with a list of script files `bmsubmit` uploads the scripts to the agent:

1. If any of the uploaded rules have the same name as an existing rule then the old rule is replaced with the new rule and all classes transformed by the rule are automatically retransformed. This includes the case where a target class was transformed but a subsequent typecheck or compile of the rule failed. This will (eventually) cause all threads executing target methods to trigger the new rule instead of the old rule. Depending upon when the compiler installs the new method code and when executing threads switch to this new code there may be a small window following the upload where neither the old nor the new rule is triggered.
2. If any of the uploaded rules apply to already loaded classes which were not previously successfully transformed (because no rule applied to them or because attempts to transform them failed) then those classes will be retransformed. Once again, depending upon when the compiler installs the new method code and when executing threads switch to this new code there may be a small window following the upload where neither the old nor the new rule is triggered.
3. Any other rules will be stored in the agents rule set and applied to newly loaded classes which match the rule.

Flag `-u` selects the uninstall mode for `bmsubmit`. When run with no arguments `bmsubmit`

uninstalls *all* currently loaded rules. When run with a list of script files `bmsubmit` uninstalls each installed rule whose name matches a rule definition contained in one of the supplied script files. `bmsubmit` does not check that rules in the supplied scripts are well formed, it merely looks for lines starting with the text `RULE`.

Flags `-b` and `-s` request installation of jar files into the bootstrap or system classpath, respectively. This is useful if rules which are to be submitted dynamically need to be provided with access to helper classes which were not in the original class path. There is no undo operation for this mode; jar files cannot be uninstalled once they have been installed. Also, it is not possible to use this option to install the byteman jar into the bootstrap classpath if it was omitted at agent startup. By the time the listener responds to this request the system class loader will already have loaded classes from the byteman jar so adding the jar to the bootstrap classpath will result in classloader conflicts.

Flag `-c` can be used to list all helper jars which have been installed by the agent into the bootstrap or system classpath.

Flag `-y` can be used to list or dynamically update the system properties which configure the operation of the Byteman agent. If no following arguments are supplied `bmsubmit` will print the value of all system properties in the agent JVM with prefix `"org.jboss.byteman."`. When arguments are supplied `bmsubmit` will set or clear the relevant system properties and notify the agent to update its configuration. If a bare property name is supplied then `bmsubmit` will unset the property. If the property name is followed by `=` and a value then the system property will be set to this value (`=` with no value sets it to an empty string). Note that for performance reasons the agent does not, by default, respond to configuration updates (this allows it to test configuration settings during operation without incurring any synchronization overhead). Dynamic configuration update must be enabled when the agent is started by setting system property `org.jboss.byteman.allow.config.updates` on the JVM command line (to any value).

n.b. Due to a bug in Sun's JDK 6 and 7 and in OpenJDK 6 and 7 errors may occur when installing a script in case 2 above (where an uploaded rule is applied to an already loaded class which has not yet been transformed). Scripts which employ references to local variables or method parameters by name will fail to compile. These JDKs retain the original bytecode for classes which are successfully transformed. However, where classes are not transformed the bytecode is discarded. When a retransform is requested the JVM's in-memory representation of the class (a C++ klass instance) is used to reconstitute the bytecode. Unfortunately the current reconstitute code does not recreate the local variable tables which were in the originally loaded bytecode. There is an OpenJDK bugzilla (#100100) and fix for this problem but the fix has not yet been incorporated into a release.

Checking Rules Offline Using Script `bmcheck`

The installed bin directory contains a script called `bmcheck` which should be used to parse and typecheck your Byteman rules offline before attempting to inject them into your application. This script uses environment variable `BYTEMAN_HOME` to locate the byteman jars needed to type check the rules. However, it still needs to be supplied with a classpath locating any application classes mentioned in the rules.

The command line syntax for the `bmcheck` script is:

```
bmcheck [-cp classpath] [-p package]* script1 [. . . scriptN]
```

Flag `-cp` provides a single classpath element used to locate classes mentioned in the scripts. If your code is located in several jars then you must supply `-cp` multiple times.

Flag `-p` provides one or more package names which are used to resolve target classes which have been specified on the `CLASS` line without a qualifying package name. For example, if a rule specifies `CLASS myClass` and the class actually resides in package `org.myApp` then the rule will be applied when class `org.myApp.myClass` is loaded during application execution. However, the type checker cannot know where to find and load the relevant class without a hint. If `-p org.myApp` is provided on the command line then after failing to locate `myClass` in the empty package the type checker will try to lookup `myClass` in package `org.myApp`. Each package supplied on the command line is tried in order until the class name can be resolved.

Installing And Submitting from Java

The scripts `bminstall` and `bmsubmit` used, respectively, to install the agent into a running program and to upload and unload scripts are merely wrappers which invoke the behaviour of Java classes, `org.jboss.byteman.agent.install.Install` and `org.jboss.byteman.agent.submit.Submit`, located, respectively, in the `byteman-install` and `byteman-submit` jars in the installed `lib` directory. The behaviour provided by these classes may be invoked from any Java program in order to load the agent or rules into the current JVM or into a remote JVM. The contributed packages provided with the Byteman release provide interesting examples of how to use this powerful capability.

Package `BMUnit` extends the `JUnit` and `TestNG` test frameworks so that they automatically install an agent and loads and unloads rules into/from the `JUnit` or `TestNG` test JVM as successive unit tests are executed. This makes it trivially easy to inject side effects such as tracing, validation code and faults into your application before running a test and then remove these side effects ready for the next test. Details of how to use `BMUnit` are provided in the 2nd of the Byteman tutorials which can be accessed from the Byteman Documentation page of the Byteman project web site located at jboss.org.

Package `DTest` allows a standalone test client to load and unload rules into/from a server JVM which allow the client to inject faults into the server code then record and validate execution of the server. Consult the Javadoc of these two API classes and the contributed package README files and source code for full details.

Environment Settings

The agent is sensitive to various environment settings which configure its behaviour.

If system property

`org.jboss.byteman.compileToBytecode`

is set (with *any* value) then the rule execution engine will compile rules to bytecode before executing them. If this property is unset it will execute rules by interpreting the rule parse tree.

Transformations performed by the agent can be observed by setting several environment variables which cause the transformed bytecode to be dumped to disk.

If system property

`org.jboss.byteman.dump.generated.classes`

is set the agent transformer code will dump a class file containing the bytecode of any class it has modified. The class file is dumped in a directory hierarchy derived from the

package of the transformed class. So, for example, class `com.arjuna.Foo` will be dumped to file `com/arjuna/Foo.class`.

If system property

`org.jboss.byteman.dump.generated.classes.directory`

is set to the name of a directory writeable by the JVM then class files will be dumped in a package directory hierarchy below this directory. For example, if this property is set with value `/tmp/dump` then class `com.arjuna.Foo` will be dumped to file `/tmp/dump/com/arjuna/Foo.class`. If this property is unset or does not identify a writeable directory then class files will be dumped below the current working directory of the JVM.

If system property

`org.jboss.byteman.dump.generated.classes.intermediate`

is set the agent will dump successive versions of transformed bytecode as successive rules applicable to a given class are injected into the bytecode.

If system property

`org.jboss.byteman.verbose`

is set then the rule execution engine will display a variety of trace messages to the `System.out` as it parses, typechecks, compiles and executes rules.

Note that the debug built-in is sensitive to this system property as well as to its own configuration switch

`org.jboss.byteman.debug`

If either of these properties is set then debug calls will print to `System.out`.

If system property

`org.jboss.byteman.transform.all`

is set then the agent will allow rules to be injected into methods of classes in the `java.lang` hierarchy. Note that this will require the Byteman jar to be installed in the bootstrap classpath using the `boot:` option to the `-javaagent` JVM command line argument.

If system property

`org.jboss.byteman.skip.overriding.rules`

is set then the agent will not perform injection into overriding method implementations. If an overriding rule is installed the agent will print a warning to `System.err` and treat the rule as if it applies only to the class named in the `CLASS` clause. This setting is not actually provided to allow rules to be misused in this way. It is a performance tuning option. The agent has to check every class as it is loaded in order to see if there are rules which apply to it. It also has to check all loaded classes when rules are dynamically loaded via the agent listener. This requires traversing the superclass chain to locate overriding rules attached to superclasses. This increases the cost of running the agent (testig indicates that the cost goes from *negligible* (<< 1%) to, at worst, *noticeable* (~ 2%) but **not** to *significant*) So, if you do not intend to use overriding rules then setting this property helps to minimise the extent to which the agent perturbs the timing of application runs. This is particularly important when testing multi-threaded applications where timing is highly significant.

If system property

org.jboss.byteman.allow.config.updates

is set (with any value) then the Byteman agent will update its configuration when changes to the value of system properties are submitted using the `bmsubmit` client with option `-y`. Note that this configuration property cannot be reset dynamically using the `submit` client. It must be set when the agent is loaded either on the JVM command line or via the `bminstall` client.

If system property

org.jboss.byteman.sysprops.strict

is set to `false` then the Byteman agent will allow the `bmsubmit` client to modify any system properties. If it is unset or set to `true` then only properties with prefix `"org.jboss.byteman."` will be modified. Note that this configuration property cannot be reset dynamically using the `bmsubmit` client. It must be set when the agent is loaded either on the JVM command line or via the `bminstall` client.