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Resource Management in Java: Tips, Traps & Techniques

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Your speaker - a short introduction ...

- Hello, I'm Neil Richards
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  - OpenJDK: neil.richards@ngmr.net
- Developing and deploying Java SDKs for 15 years
- Previous IBM technical component lead:
  - IO
  - Networking
  - ORB, CORBA, RMI-IIOP
- Currently working for IBM in OpenJDK
  - OpenJDK 8
  - OpenJDK 7u
  - Common VM Interface
  - AIX/PPC porting

So, what shall we talk about?

- What resources need managing ?
- Definitions
- Explore some approaches ...
  - "Passive", "Active" & "Hybrid"
  - How to use
  - Potential pitfalls (aka "Traps")
  - Worked examples
  - Limitations
- Recommendations

What resources need managing ?

	C/C++	Java
Stack memory	Automatic	Automatic*
Heap memory	Manual	Automatic**
File descriptor	Manual	Manual
Network socket	Manual	Manual
Database connection	Manual	Manual
etc.	Manual	Manual

* NB: No stack-based object allocation in Java (except via JIT magic)

** NB: C/C++ heap memory management in a Java process is still manual

Definitions

"When I use a word,"
Humpty Dumpty said, in a rather scornful tone,
"it means just what I choose it to mean -
neither more nor less."

Lewis Carroll

- "Passive" management:
  - Places no requirements on the end user (developer) as to how the Java objects representing the resource are handled.
- "Active" management:
  - Places requirements on the end user (developer) as to how the Java objects representing the resource are handled.

Passive approach #1 - Finalization

Finalizers provide a chance to free up resources that cannot be freed automatically by an automatic storage manager.

♦

Before the storage for an object is reclaimed by the garbage collector, the Java virtual machine will invoke the finalizer of that object.

JLS, Java SE 7 Edition, section 12.6

- Override: `protected void Object.finalize() throws Throwable;`

Passive approach #1 – Finalization: Traps (part 1)

The Java programming language imposes no ordering on `finalize` method calls. Finalizers may be called in any order, or even concurrently.

♦

If an uncaught exception is thrown during the finalization, the exception is ignored and finalization of that object terminates.

♦

Unlike constructors, finalizers do not automatically invoke the finalizer for the superclass; such an invocation must be coded explicitly.
`<snip>` This should always be done …

♦

A finalizer may be invoked explicitly, just like any other method.

JLS, Java SE 7 Edition, section 12.6

- Usage usually gets exposed / baked into the class' API

Passive approach #1 – Finalization: Traps (part 2)

- Only implementable by developer of the resource class
- In `finalize()`, developer still has access to the object ('`this`')
  - –> Has access to other objects referenced by '`this`'
    - already finalized ?
    - in the midst of being finalized ?
    - scheduled to be (unavoidably) finalized ?
  - –> Lots of temptation / possibility to use “stale” data, objects
    - or even try to “resurrect” them ...

- `finalize()` might be called on an object multiple times …
  - – but only **once** from finalization!

Passive approach #1 – Finalization: example

```
public class MyResource1 {
    private final long handle;
    private final java.util.concurrent.atomic.AtomicBoolean closed = new java.util.concurrent.atomic.AtomicBoolean();

    public MyResource1(/*params*/) throws Throwable {
        handle = allocNativeResource(/*params*/);
    }

    protected void finalize() throws Throwable {
        try {
            Throwable saved = null;
            try {
                if (closed.compareAndSet(false, true)) freeNativeResource(handle);
            } catch (Exception e) {
                saved = e;
            } finally {
                try {
                    super.finalize();
                } catch (Throwable t) {
                    if (saved == null) throw t;
                    saved.addSuppressed(t);
                }
                if (saved != null) throw saved;
            }
        } catch (Throwable t2) {
            t2.printStackTrace();
            throw t2;
        }
    }

    private static native long allocNativeResource(/*params*/) throws Exception;
    private static native void freeNativeResource(long handle) throws Exception;
}
```

Passive approach #2 – java.lang.ref.PhantomReference

Phantom reference objects, which are enqueued after the collector determines that their referents may otherwise be reclaimed.

♦

Phantom references are most often used for scheduling pre-mortem cleanup actions in a more flexible way than is possible with the Java finalization mechanism.

Java 7 API Javadoc

- Create 2nd "Reference" class, subclassing PhantomReference
  - Used for tracking main "Resource" objects
- Create statically held ReferenceQueue object
  - Source of "stale" reference objects to be processed
  - "stale" references removed from queue by:
    - calling `poll()`, usually before each operation
    - calling `remove()`, blocking on dedicated thread

Passive approach #2 – PhantomReferences: Traps

If the garbage collector determines at a certain point in time that the referent of a phantom reference is phantom reachable, then at that time **or at some later time** it will enqueue the reference.

♦

The `get` method of a phantom reference always returns `null`.

♦

An object that is reachable via phantom references will remain so until all such references are cleared or themselves become unreachable.

Java 7 API Javadoc

- Strong reference must be maintained to the Reference objects
  - Must be freed once stale reference is processed

Passive approach #2 – PhantomReferences: Benefits

The `get` method of a phantom reference always returns `null`.

Java 7 API Javadoc

- No interference with finalization / PhantomReference use in superclasses (and elsewhere)
  –> Avoids complicated coding for exception handling
- Possibility of implementing PhantomReferences “external” to resource being tracked
  – Will examine this more later ...

Passive approach #2 – PhantomReference: example (part 1)

```
public class MyResource2 {
    private static class MyResourceRef extends java.lang.ref.PhantomReference<MyResource2> {
        private static final java.util.Set<MyResourceRef> activeRefs = new java.util.HashSet<>();
        private static final java.lang.ref.ReferenceQueue<MyResource2> staleRefs = new java.lang.ref.ReferenceQueue<>();
        final long handle;

        MyResourceRef(MyResource2 myRes /*, params*/) throws Exception {
            super(myRes, staleRefs);
            handle = allocNativeResource(/*params*/);

            synchronized (activeRefs) {
                activeRefs.add(this);
            }
        }

        private boolean deactivate() {
            synchronized (activeRefs) {
                return activeRefs.remove(this);
            }
        }

        final void close() throws Exception {
            if (deactivate()) freeNativeResource(handle);
        }

        private static native long allocNativeResource(/*params*/) throws Exception;
        private static native void freeNativeResource(long handle) throws Exception;

        static void processQ() { /*...*/ }
    }

    /*...*/
}
```

Passive approach #2 – PhantomReference: example (part 2)

```
public class MyResource2 {
    private static class MyResourceRef extends java.lang.ref.PhantomReference<MyResource2> {
        private static final java.util.Set<MyResourceRef> activeRefs = new java.util.HashSet<>();
        private static final java.lang.ref.ReferenceQueue<MyResource2> staleRefs = new java.lang.ref.ReferenceQueue<>();
        final long handle;

        /*...*/

        static void processQ() {
            MyResourceRef staleRef = null;
            do {
                synchronized (staleRefs) {
                    staleRef = (MyResourceRef)staleRefs.poll();
                }
                if (staleRef == null) break;
                try {
                    staleRef.close();
                } catch (Exception e) {
                    e.printStackTrace();
                }
            } while (true);
        }
    }

    private final MyResourceRef ref;

    public MyResource2(/*params*/) throws Exception {
        ref = new MyResourceRef(this /*, params*/);
    }

    public void doSomething() {
        MyResourceRef.processQ();
        /* do something with 'handle' */
    }
}
```

Passive approach #2 – PhantomReference: example2

```
public class MyResource2v2 {
    private static class MyResourceRef extends java.lang.ref.PhantomReference<MyResource2v2> {
        /*...*/

        MyResourceRef(MyResource2v2 myRes /*, params*/) throws Exception {
            super(myRes, Reaper.staleRefs);
            /*...*/
        }

        //processQ() no longer needed

        private static final class Reaper extends Thread {
            static final Reaper thread = new Reaper();
            static final java.lang.ref.ReferenceQueue<MyResource2v2> staleRefs = new java.lang.ref.ReferenceQueue<>();

            static {
                thread.setDaemon(true);
                thread.start();
            }

            public void run() {
                do {
                    try {
                        MyResourceRef staleRef = (MyResourceRef)staleRefs.remove();
                        staleRef.close();
                    } catch (InterruptedException ie) {
                    } catch (Exception e) {
                        e.printStackTrace();
                    }
                } while (true);
            }
        }
    }
}
```

Passive approaches: General limitations

- Resources can only found as “stale” once GC occurs
  - – GC might be “conservative”
  - –> No guarantee stale resources are found even after GC
- GC generally triggered by constraint of Java heap memory (i.e. another resource type), so:
  - – Larger Java heap
  - –> Longer wait for other resources to be closed
  - –> Greater risk of OOME due to other resource exhaustion
- GC releasing the memory of resource Java objects delayed
  - – Finalizable objects processed by finalization thread(s)
  - – Reference removed from ReferenceQueue, processed
  - –> More constrained Java heap usage
  - –> More time spent performing GC

Active approach #1 – Management by fiat

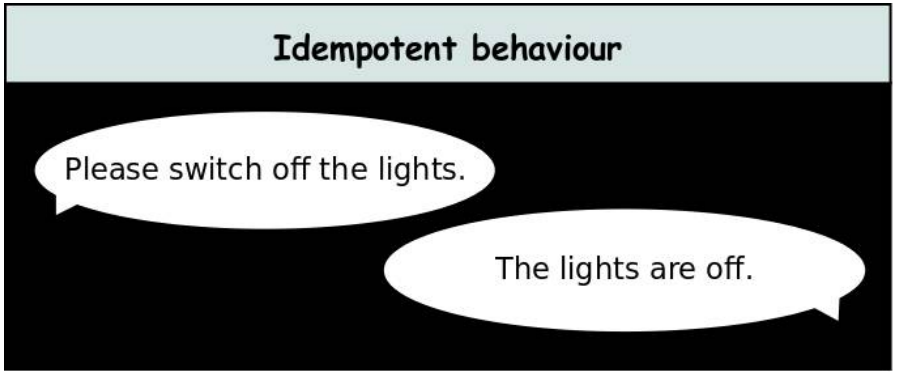
fi•at n.

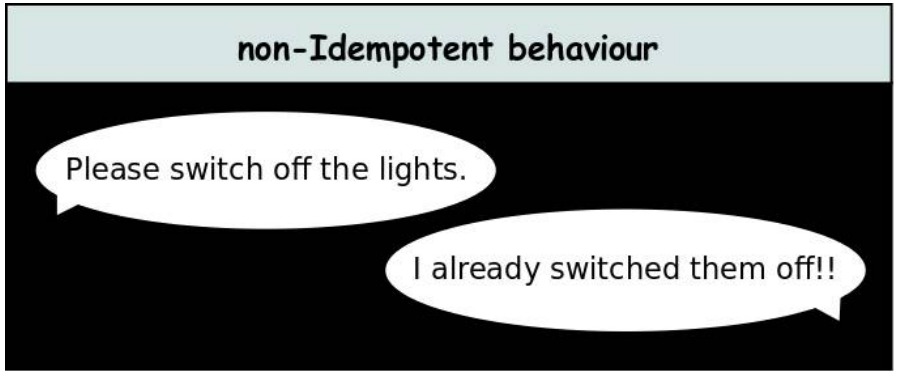
1. An arbitrary order or decree.

www.freedictionary.com

- Provide a method on resource object to release the underlying resource
  - Generally called `public void close() throws Exception;`
- Decree in the Javadoc that users must call the method to free the native resource.
- Tip: Helpful if function is “idempotent”

Sidebar: Idempotency





i•dem•po•tent adj.

(computing) Describing an action which, when performed multiple times, has no further effect on its subject after the first time it is performed.

en.wiktionary.org

- Recommendation: Make closing all resources idempotent

Active approach #1 – Management by fiat: Traps

- Relies upon end user calling `close()`.
- Tricky for user to ensure `close()` is always called at the correct moment.
  - Tip: Use try-finally blocks where possible
- Complexity explosion properly handling exceptions when closing several resources at the same time.

Active approach #1 – Management by fiat: example

```
public class MyResource3User {
    public static void main(String[] args) throws Exception {
        MyResource3 myRes = new MyResource3(/*params*/);
        try {
            /* do stuff using 'myRes' */
        } finally {
            myRes.close();
        }
    }

    public static class MyResource3 {
        private final long handle;
        private final java.util.concurrent.atomic.AtomicBoolean closed =
            new java.util.concurrent.atomic.AtomicBoolean();

        public MyResource3(/*params*/) throws Exception {
            handle = allocNativeResource(/*params*/);
        }

        /** Closes the resource. This MUST be called by the user. */
        public void close() throws Exception {
            if (closed.compareAndSet(false, true)) freeNativeResource(handle);
        }

        private static native long allocNativeResource(/*params*/) throws Exception;
        private static native void freeNativeResource(long handle) throws Exception;
    }
}
```

Active approach #2 – ARM (try-with-resources)

- try-with-resources, aka Automatic Resource Management (ARM)
- Introduced in Java SE 7 (best feature **ever** ?)
- Implement: `java.lang.AutoCloseable`
  –> `public void close() throws Exception;`
- AutoCloseable objects assigned within parentheses of try statement are automatically closed at the end of that try block
  - Automatic (implicit) generation of `finally` logic to close resources, correctly deal with exception handling
  - Support for multiple assignments in same `try` block

Active approach #2 – ARM (try-with-resources): Traps

- Needs user compliance to use try-with-resources syntax
  - Though user may call `close()` method directly instead
    - Loses exception handling “magic”
- AutoCloseable objects **assigned** within parentheses of try statement are automatically closed at the end of that try block
  –> AutoCloseable objects allocated in try statement not automatically closed (unless also assigned)
- Needs Java SE 7

Active approach #2 – ARM (try-with-resources): example

```
public class MyResource4User {
    public static void main(String[] args) throws Exception {
        try (MyResource4 myRes1 = new MyResource4(/*params*/);
                MyResource4 myRes2 = new MyResource4(/*params*/)) {
            /* do stuff using 'myRes1', 'myRes2' */
        }
    }

    public static class MyResource4 implements AutoCloseable {
        private final long handle;
        private final java.util.concurrent.atomic.AtomicBoolean closed =
            new java.util.concurrent.atomic.AtomicBoolean();

        public MyResource4(/*params*/) throws Exception {
            handle = allocNativeResource(/*params*/);
        }

        /** Closes the resource. This MUST be called by the user, optionally by using try-with-resources. */
        public void close() throws Exception {
            if (closed.compareAndSet(false, true)) freeNativeResource(handle);
        }

        private static native long allocNativeResource(/*params*/) throws Exception;
        private static native void freeNativeResource(long handle) throws Exception;
    }
}
```

Active approaches: General limitations

- Resources may be visible to “normal” code when closed
  –> Guard checking needed in each resource operation
- No guarantees user will follow instructions!!!
- **No guarantees user will follow instructions!!!**

Hybrid approach – Getting the best of both worlds

- Use active approach to allow timely freeing of resource by user
- Use passive approach to verify user is freeing resources

Combined approach: example (part 1)

```
public class MyResource5 implements AutoCloseable {
    private final long handle;
    private final MyResourceRef ref;

    private static class MyResourceRef extends java.lang.ref.PhantomReference<Object> {
        private static final java.util.Set<MyResourceRef> activeRefs = new java.util.HashSet<>();
        final Exception leakException;

        MyResourceRef(Object myRes) throws Exception {
            super(myRes, Reaper.staleRefs);
            leakException = new Exception("Resource leak detected - resource allocation call stack:");
            synchronized (activeRefs) {
                activeRefs.add(this);
            }
        }

        final boolean deactivate() { /* as before */ }

        private static final class Reaper extends Thread { /*...*/ }
    }

    public MyResource5(/*params*/) throws Exception {
        handle = allocNativeResource(/*params*/);
        ref = new MyResourceRef(this);
    }

    /** Closes the resource. This MUST be called by the user, optionally by using try-with-resources. */
    public void close() throws Exception {
        if (ref.deactivate()) freeNativeResource(handle);
    }

    private static native long allocNativeResource(/*params*/) throws Exception;
    private static native void freeNativeResource(long handle) throws Exception;
}
```

Combined approach: example (part 2)

```
public class MyResource5 implements AutoCloseable {
    private final long handle;
    private final MyResourceRef ref;

    private static class MyResourceRef extends java.lang.ref.PhantomReference<Object> {
        final Exception leakException;

        /*...*/

        private static final class Reaper extends Thread {
            private static final Reaper thread = new Reaper();
            static final java.lang.ref.ReferenceQueue<Object> staleRefs = new java.lang.ref.ReferenceQueue<>();

            static {
                thread.start();
            }

            private Reaper() {
                setDaemon(true);
            }

            public void run() {
                do {
                    try {
                        MyResourceRef staleRef = (MyResourceRef)staleRefs.remove();
                        if (staleRef.deactivate()) {
                            staleRef.leakException.printStackTrace();
                        }
                    } catch (InterruptedException ie) {}
                } while (true);
            }
        }
    }
}
```

Recommendations

- Use “Active” approach
  - Use to allow user to swiftly free resources
  - Implement AutoCloseable
    - Allows user to safely free resources using ARM
- Use “Passive” approach
  - Use to monitor resources are correctly freed by user
    - Even for key “standard” Java resources ?
  - Use PhantomReference over Finalization
    - Ease of correct implementation
    - Flexibility
  - Fail-fast if resource leakage is detected
- Use both approaches in combination
  - Allow user to free resources in a timely manner
  - Monitor for & Report resource leakage

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