



The Ghost in the Virtual Machine

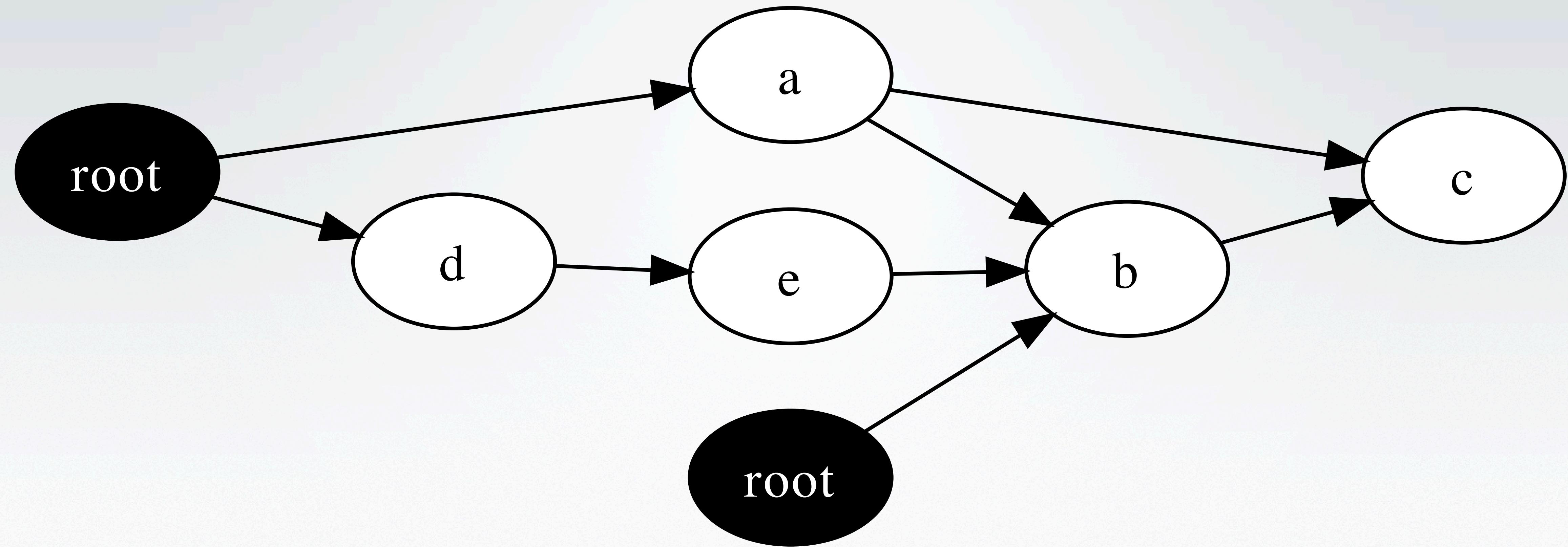
A Reference to References

Bob Lee
Square Inc.

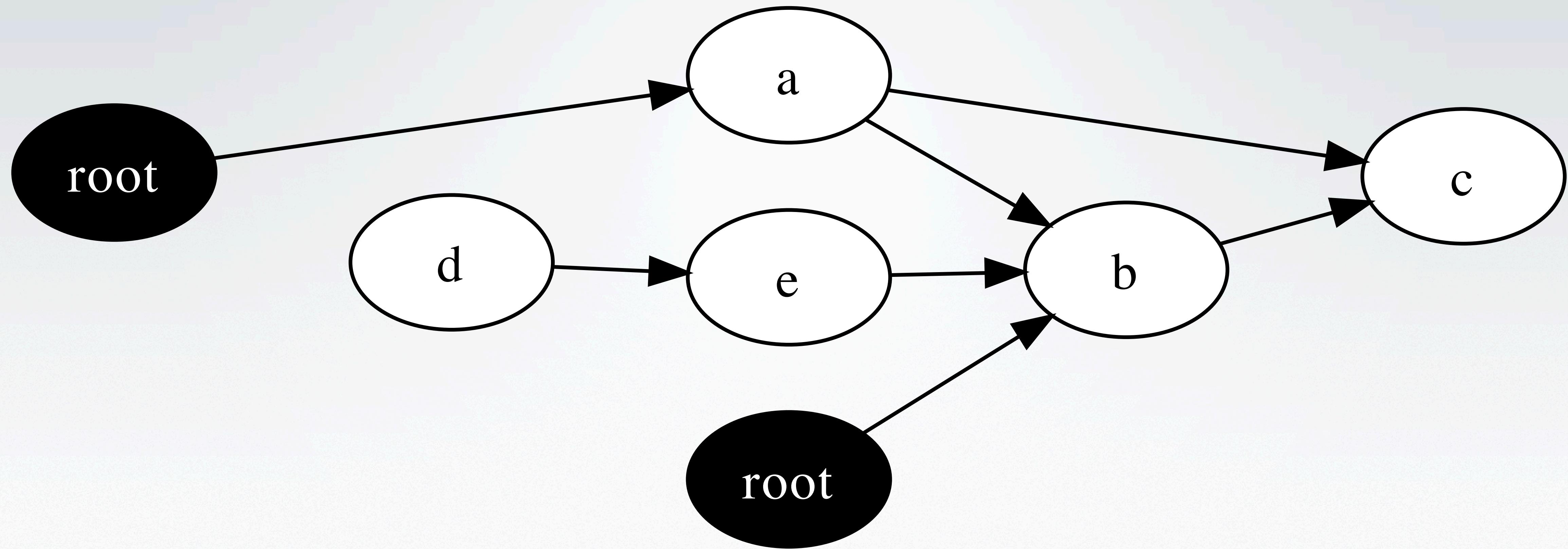
Goals

- Take the mystery out of garbage collection.
- Put an end to finalizers.
- Perform manual cleanup the Right Way.

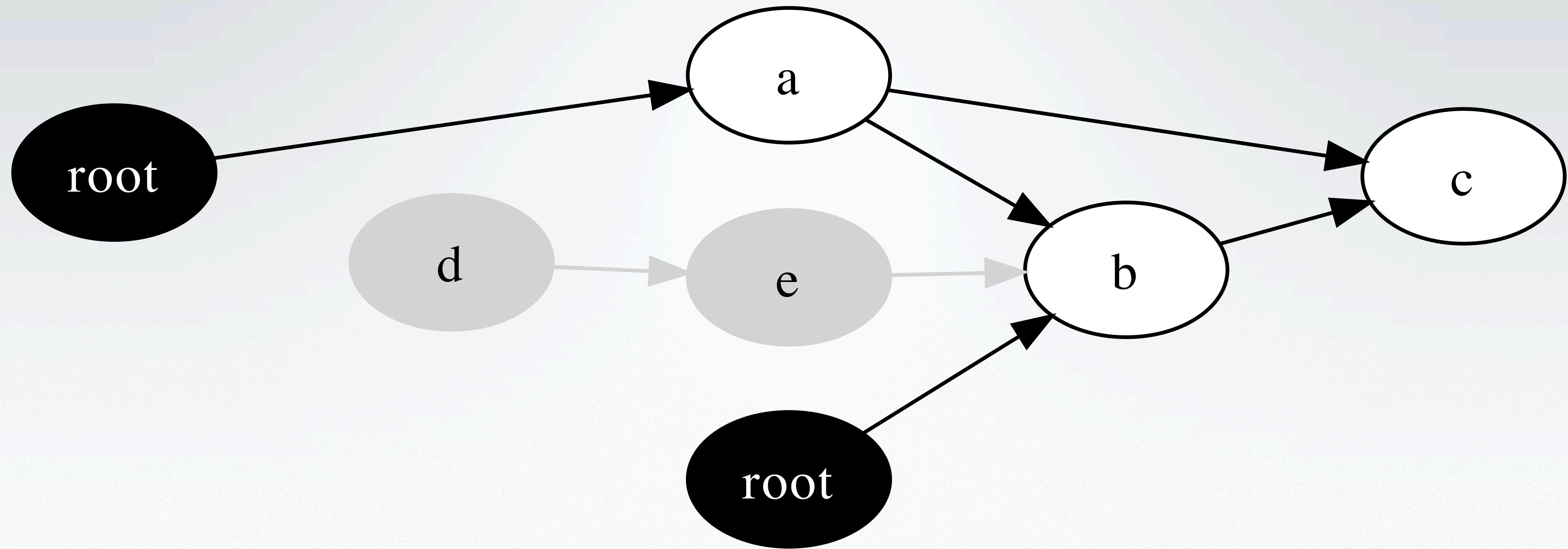
How does garbage collection work?



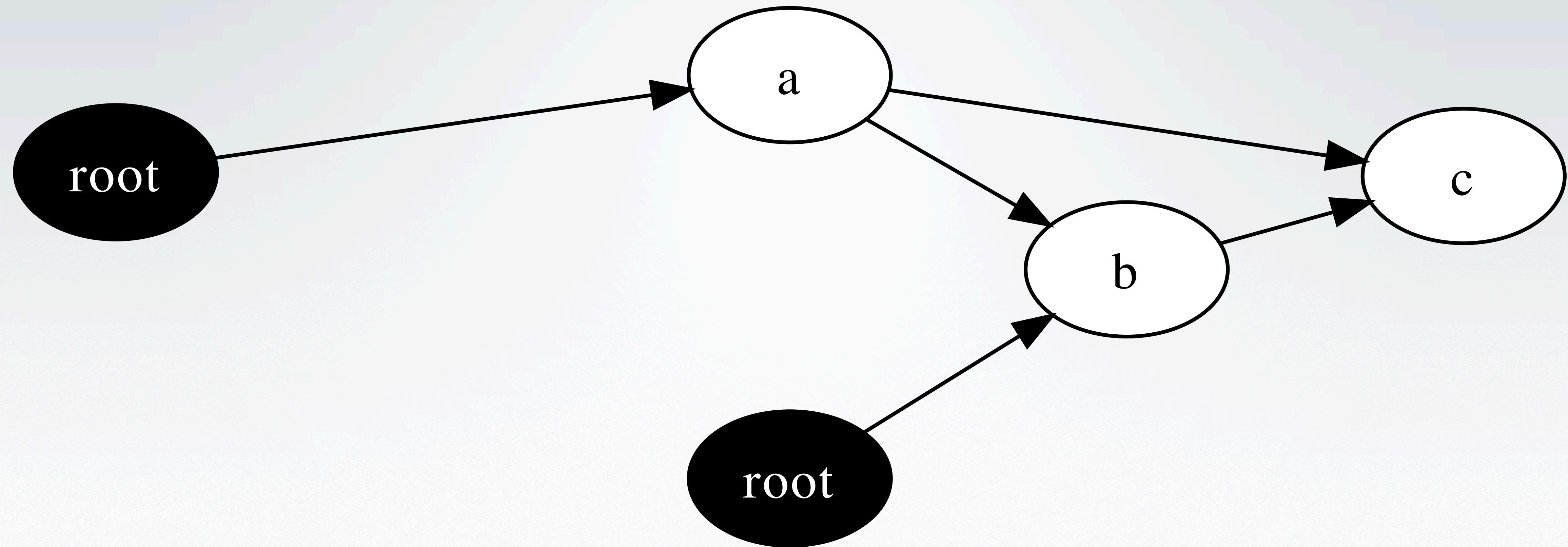
If the reference to D goes away...



We can no longer reach D or E.



So the collector reclaims them.



Reachability

- An object is *reachable* if a live thread can access it.
- Examples of heap roots:
 - System classes (which have static fields)
 - Thread stacks
 - In-flight exceptions
 - JNI global references
 - The finalizer queue
 - The interned String pool
 - etc. (VM-dependent)

Garbage collection isn't a magic bullet.

- Some things require manual cleanup.
 - Listeners
 - File descriptors
 - Native memory
 - External state (**IdentityHashMap**)
- Tools at your disposal:
 - try-finally
 - Overriding **Object.finalize()**
 - References (and reference queues)

Try-finally first.

```
public static void copy(File file, OutputStream out) throws IOException {
    byte[] buffer = new byte[4096];
    FileInputStream in = new FileInputStream(file);
    try {
        int read;
        while ((read = in.read(buffer)) >= 0) out.write(buffer, 0, read);
    } finally {
        in.close();
    }
}
```

Try-finally first.

- Pros:
 - More straightforward
 - Handles exceptions in main thread
 - Ensures cleanup keeps pace
- Cons:
 - More work for programmers
 - More error prone
 - Cleanup happens in main thread
- Try-with-resources will help.

Try-with-resources

Before:

```
public static void copy(File file, OutputStream out) throws IOException {
    byte[] buffer = new byte[4096];
    FileInputStream in = new FileInputStream(file);
    try {
        int read;
        while ((read = in.read(buffer)) >= 0) out.write(buffer, 0, read);
    } finally {
        in.close();
    }
}
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Try-with-resources

Before:

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public static void copy(File file, OutputStream out) throws IOException {
    byte[] buffer = new byte[4096];
    FileInputStream in = new FileInputStream(file);
    try {
        int read;
        while ((read = in.read(buffer)) >= 0) out.write(buffer, 0, read);
    } finally {
        in.close();
    }
}
```

After:

```
public static void copy(File file, OutputStream out) throws IOException {
    byte[] buffer = new byte[4096];
    try (FileInputStream in = new FileInputStream(file)) {
        int read;
        while ((read = in.read(buffer)) >= 0) out.write(buffer, 0, read);
    }
}
```

What is a finalizer?

A callback used by the garbage collector to notify an object when it is about to be reclaimed:

```
public class Foo extends Bar {  
    @Override protected void finalize() throws Throwable {  
        try {  
            ... // Clean up Foo.  
        } finally {  
            super.finalize(); // Clean up Bar.  
        }  
    }  
}
```

Finalizers are seductively simple, but...

- They're not guaranteed to run, especially not timely.
- Undefined threading model; they can run concurrently!
- You must remember to call `super.finalize()`.
- Exceptions are ignored (per spec).
- You can resurrect references.
- They keep objects alive longer than necessary.
- They can make allocation/reclamation 430X slower!
(Bloch, *Effective Java*)
- Worst of all, they messed up the reference API.

Example

```
public class NativeMemory {
    final int address = allocate();
    /** Allocates native memory. */
    static native int allocate();

    /** Writes to native memory. */
    public void write(byte[] data) {
        write(address, data);
    }
    static native void write(int address, byte[] data);

    /** Frees native memory. */
    @Override protected void finalize() {
        free(address);
    }
    static native void free(int address);
}
```

Let's play War!

SegfaultFactory can cause a segfault if its finalizer executes after **NativeMemory**'s:

```
public class SegfaultFactory {
    private final NativeMemory nm;

    public SegfaultFactory(NativeMemory nm) {
        this.nm = nm;
    }

    @Override protected void finalize() {
        // 50/50 chance of failure
        nm.write("I'm taking the VM with me!".getBytes());
    }
}
```



Always use protection.

```
public class NativeMemory {
    final int address = allocate();
    /** Allocates native memory. */
    static native int allocate();

    /** Writes to native memory. */
    boolean finalized;
    public synchronized void write(byte[] data) {
        if (!finalized) write(address, data);
        else /* do nothing? */;
    }
    static native void write(int address, byte[] data);

    /** Frees native memory. */
    @Override protected synchronized void finalize() {
        finalized = true;
        free(address);
    }
    static native void free(int address);
}
```

Basically, finalizers are good for one thing.

Logging warnings:

```
public class Connection {  
    ...  
    boolean closed;  
    public synchronized void close() {  
        reallyClose();  
        closed = true;  
    }  
    private native void reallyClose();  
  
    @Override protected synchronized void finalize() {  
        if (!closed) {  
            Logger.getLogger(Connection.class.getName())  
                .warning("You forgot to close me!!!");  
            close();  
        }  
    }  
}
```

Basically, finalizers are good for one thing.

Logging warnings:

```
public class Connection {  
    ...  
    boolean closed;  
    public synchronized void close() {  
        reallyClose();  
        closed = true;  
    }  
    private native void reallyClose();  
  
    @Override protected synchronized void finalize() {  
        if (!closed) {  
            Logger.getLogger(Connection.class.getName())  
                .warning("You forgot to close me!!!");  
            close();  
        }  
    }  
}
```

Unless you want to disable the warnings.

The alternative: The Reference API

- **@since 1.2**
- Reference types
 - **Soft**: for caching
 - **Weak**: for fast cleanup (pre-finalizer)
 - **Phantom**: for safe cleanup (post-finalizer)
- **Reference queues**: for notifications

package java.lang.ref

```
public abstract class Reference<T> {
    public T get() { ... }
}

public class SoftReference<T> extends Reference<T> {
    public SoftReference(T referent) { ... }
    public SoftReference(T referent, ReferenceQueue<? super T> q) { ... }
}

public class WeakReference<T> extends Reference<T> {
    public WeakReference(T referent) { ... }
    public WeakReference(T referent, ReferenceQueue<? super T> q) { ... }
}

public class PhantomReference<T> extends Reference<T> {
    public PhantomReference(T referent, ReferenceQueue<? super T> q) { ... }
}

public class ReferenceQueue<T> {
    public ReferenceQueue() { ... }
    public Reference<? extends T> poll() { ... }
    public Reference<? extends T> remove() { ... }
}
```

Soft references

- Cleared when the VM runs low on memory
 - *Hopefully* in LRU fashion
- Tuned with **-XX:SoftRefLRUPolicyMsPerMB**
 - How long to retain soft refs in *ms per free MB of heap*
 - Default: 1000ms

Use soft references judiciously.

- For quick-and-dirty caching only
- Soft refs have no notion of *weight*.
 - Memory usage
 - Computation time
 - CPU usage
- Soft refs can exacerbate low memory conditions.

Caching a file

```
public class CachedFile {
    final File file;
    public CachedFile(File file) {
        this.file = file;
    }
    volatile SoftReference<byte[]> dataReference
        = new SoftReference<byte[]>(null);
    /** Gets file contents, reading them if necessary. */
    public byte[] getData() {
        byte[] data = dataReference.get();
        if (data != null) return data;
        data = readData();
        dataReference = new SoftReference<byte[]>(data);
        return data;
    }
    /** Reads file contents. */
    byte[] readData() {
        ...
    }
}
```

Caching a file

```
public class CachedFile {  
    final File file;  
    public CachedFile(File file) {  
        this.file = file;  
    }  
    volatile SoftReference<byte[]> dataReference  
        = null;  
    /** Gets file contents, reading them if necessary. */  
    public byte[] getData() {  
        byte[] data = dataReference.get();  
        if (data == null) return data;  
        data = readData();  
        dataReference = new SoftReference<byte[]>(data);  
        return data;  
    }  
    /** Reads file contents. */  
    byte[] readData() {  
        ...  
    }  
}
```

Weak references

- Cleared as soon as no strong or soft refs remain.
- Cleared ASAP, before the finalizer runs.
- **Not for caching!** Use soft references, as intended:

“Virtual machine implementations are encouraged to bias against clearing recently-created or recently-used soft references.”

- The `SoftReference` documentation

Can you hear me now?

```
public class Button {  
    public interface Listener {  
        void onClick();  
    }  
    private final List<WeakReference<Listener>> listeners  
        = new ArrayList<WeakReference<Listener>>();  
    public void add(Listener l) {  
        listeners.add(new WeakReference<Listener>(l));  
    }  
    public void click() {  
        Iterator<WeakReference<Listener>> i  
            = listeners.iterator();  
        while (i.hasNext()) {  
            Listener l = i.next().get();  
            if (l == null) i.remove();  
            else l.onClick();  
        }  
    }  
}
```

Phantom references

- Enqueued after no other references remain, *post-finalizer*.
 - Can suffer similar problems to finalizers.
- Must be cleared manually, for no good reason.
- `get()` always returns `null`.
 - So you must use a reference queue.

Let's replace a finalizer!

```
public class NativeMemory {
    final int address = allocate();
    /** Allocates native memory. */
    static native int allocate();
    NativeMemory() {}

    /** Writes to native memory. */
    public void write(byte[] data) {
        write(address, data);
    }
    static native void write(int address, byte[] data);

    /** Frees native memory. */
    @Override protected void finalize() {
        free(address);
    }
    static native void free(int address);
}
```

The reference

```
class NativeMemoryReference
    extends PhantomReference<NativeMemory> {
    final int address;
    NativeMemoryReference(NativeMemory referent,
        ReferenceQueue<NativeMemory> rq) {
        super(referent, rq);
        address = referent.address;
    }
}
```

The manager

```
public class NativeMemoryManager {  
    private static final Set<Reference<?>> refs  
        = Collections.synchronizedSet(new HashSet<Reference<?>>());  
    private static final ReferenceQueue<NativeMemory> rq  
        = new ReferenceQueue<NativeMemory>();  
    public static NativeMemory allocate() {  
        NativeMemory nm = new NativeMemory();  
        refs.add(new NativeMemoryReference(nm, rq));  
        cleanUp();  
        return nm;  
    }  
    private static void cleanUp() {  
        NativeMemoryReference ref;  
        while ((ref = (NativeMemoryReference) rq.poll()) != null) {  
            NativeMemory.free(ref.address);  
            refs.remove(ref);  
        }  
    }  
}
```

The manager *with* the Guava Libraries

```
public class NativeMemoryManager {  
    private static final Set<Reference<?>> refs  
        = Collections.synchronizedSet(new HashSet<Reference<?>>());  
    private static final FinalizableReferenceQueue frq  
        = new FinalizableReferenceQueue();  
    public static NativeMemory allocate() {  
        NativeMemory nm = new NativeMemory();  
        final int address = nm.address;  
        refs.add(new FinalizablePhantomReference<NativeMemory>(nm, frq) {  
            public void finalizeReferent() {  
                NativeMemory.free(address);  
                refs.remove(this);  
            }  
        });  
        return nm;  
    }  
}
```

Tip: accessing a phantom referent

```
public class WeakPhantomReference<T> extends PhantomReference<T> {  
    final WeakReference<T> weakReference;  
  
    public WeakPhantomReference(T referent,  
        ReferenceQueue<? super T> q) {  
        super(referent, q);  
        weakReference = new WeakReference<T>(referent);  
    }  
  
    /** Returns referent so long as it's weakly-reachable. */  
    @Override public T get() {  
        return weakReference.get();  
    }  
}
```

Don't forget...

The GC runs concurrently with your code:

```
public class RaceTheCollector {  
    public <T> T dereference(WeakReference<T> referent) {  
        T t = referent.get();  
        if (t == null) {  
            throw new NullPointerException("Reference is cleared.");  
        }  
        ... // The garbage collector runs.  
        return referent.get(); // Can return null!!!  
    }  
}
```

`java.util.WeakHashMap`

- Useful for emulating additional fields
- Keeps weak refs to keys, strong refs to values
- Not concurrent
- Uses `equals()` when it should use `==`

Guava MapMaker

- Near drop-in replacement for **WeakHashMap**
- Strong, soft, or weak key and/or value references
- Uses `==` to compare weak and soft referents

Guava CacheBuilder

- Superset of **MapMaker**
- Supports on-demand computation of values
- Expiration
- Size limiting

Guava CacheBuilder

```
public class GetterMethods {  
    final static Cache<Class<?>, List<Method>> cache = CacheBuilder.newBuilder()  
        .weakKeys()  
        .softValues()  
        .build(new CacheLoader<Class<?>, List<Method>>() {  
            public List<Method> load(Class<?> clazz) {  
                List<Method> getters = new ArrayList<Method>();  
                for (Method m : clazz.getMethods())  
                    if (m.getName().startsWith("get"))  
                        getters.add(m);  
                return getters;  
            }  
        });  
    public static List<Method> on(Class<?> clazz) {  
        return cache.apply(clazz);  
    }  
}
```

Usage: `List<Method> l = GetterMethods.on(Foo.class);`

Recap: The Levels of Reachability

- Strong
- Soft
- Weak
- Finalizer
- Phantom, JNI weak
- Unreachable

Recap: The Levels of Reachability

- **Strong**
- Soft
- Weak
- Finalizer
- Phantom, JNI weak
- Unreachable

Recap: The Levels of Reachability

- Strong
- **Soft**
- Weak
- Finalizer
- Phantom, JNI weak
- Unreachable

Recap: The Levels of Reachability

- Strong
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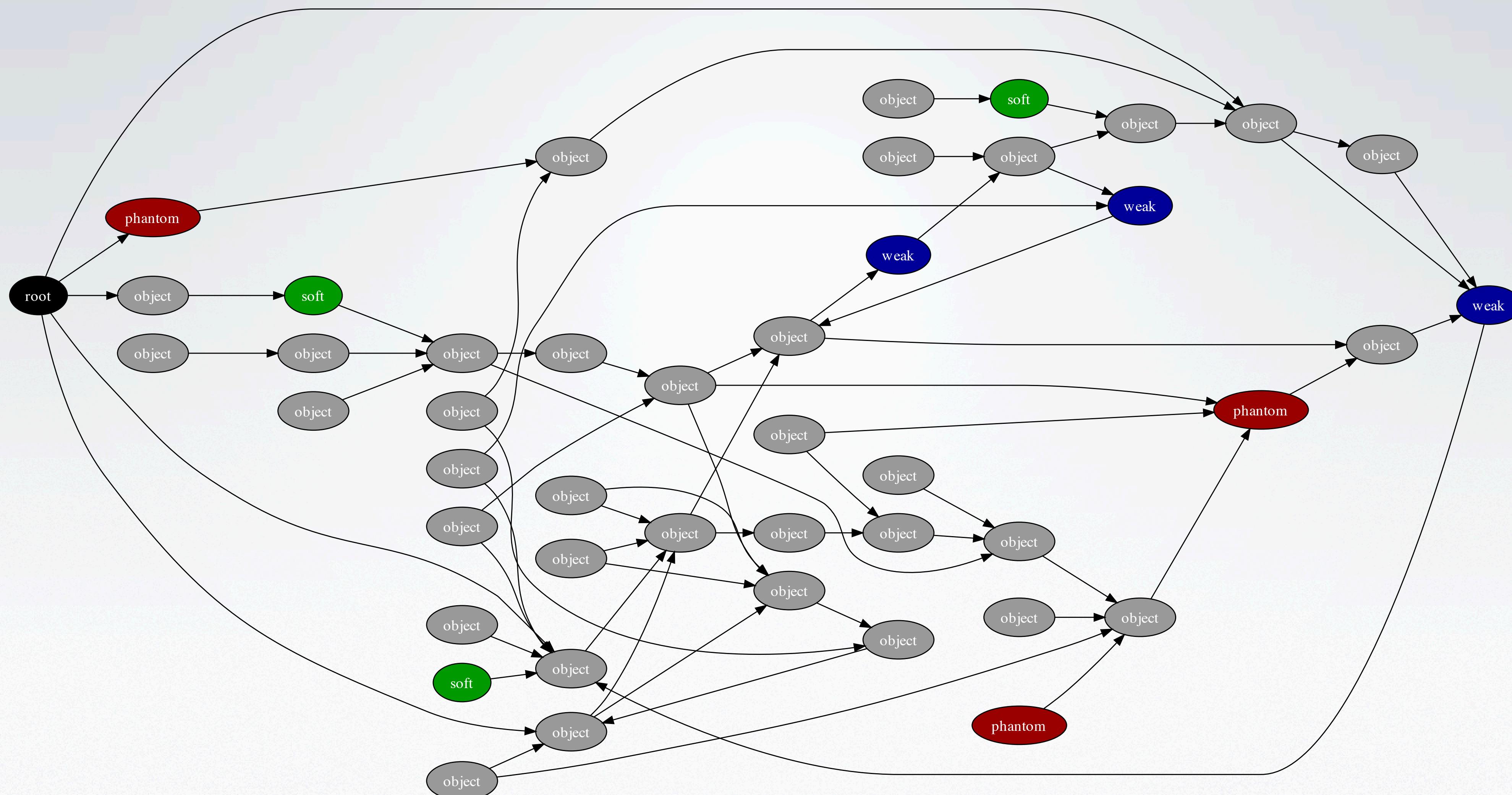
Recap: The Levels of Reachability

- Strong
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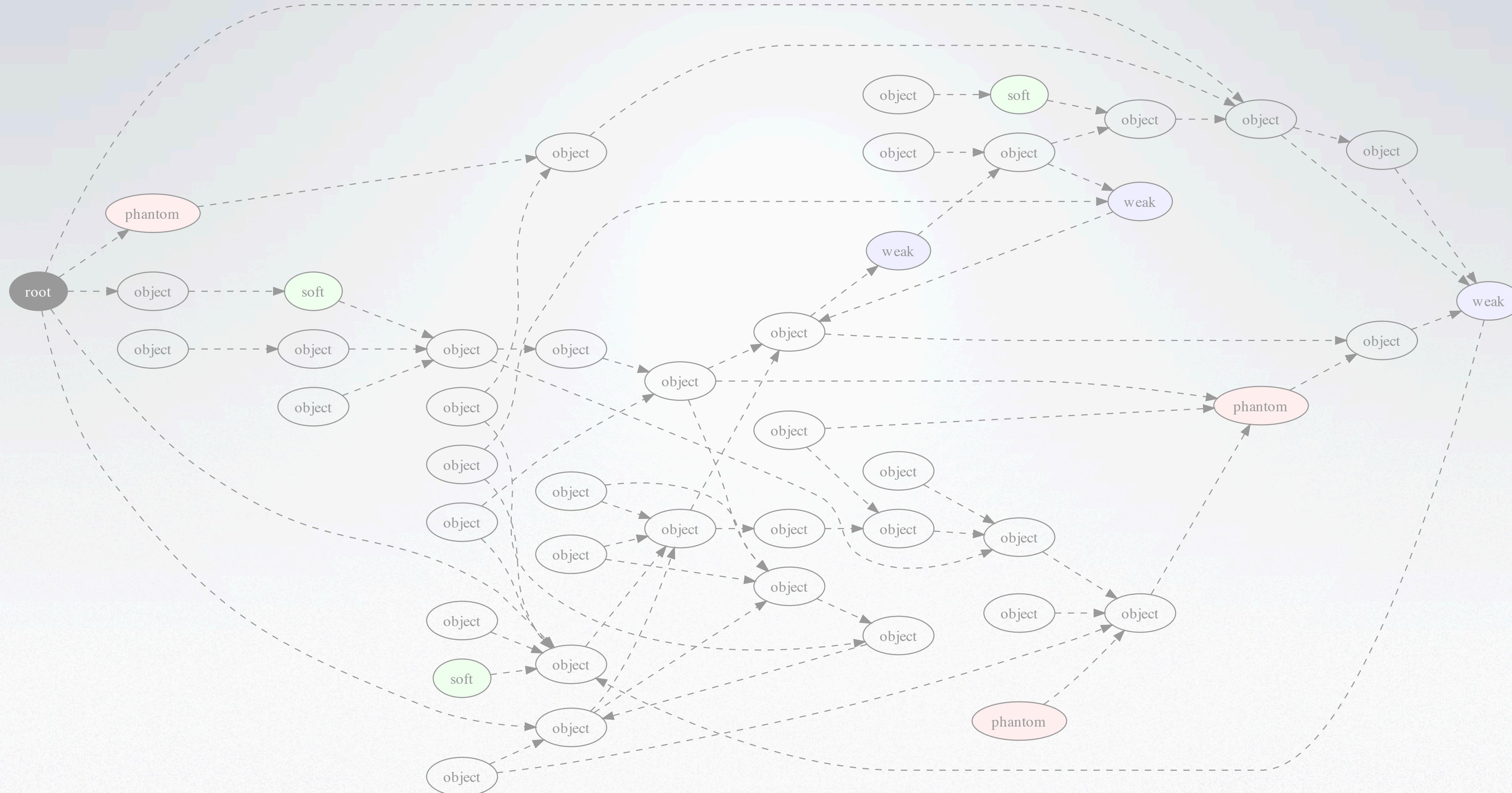
Recap: The Levels of Reachability

- Strong
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- Finalizer
- Phantom, JNI weak
- **Unreachable**

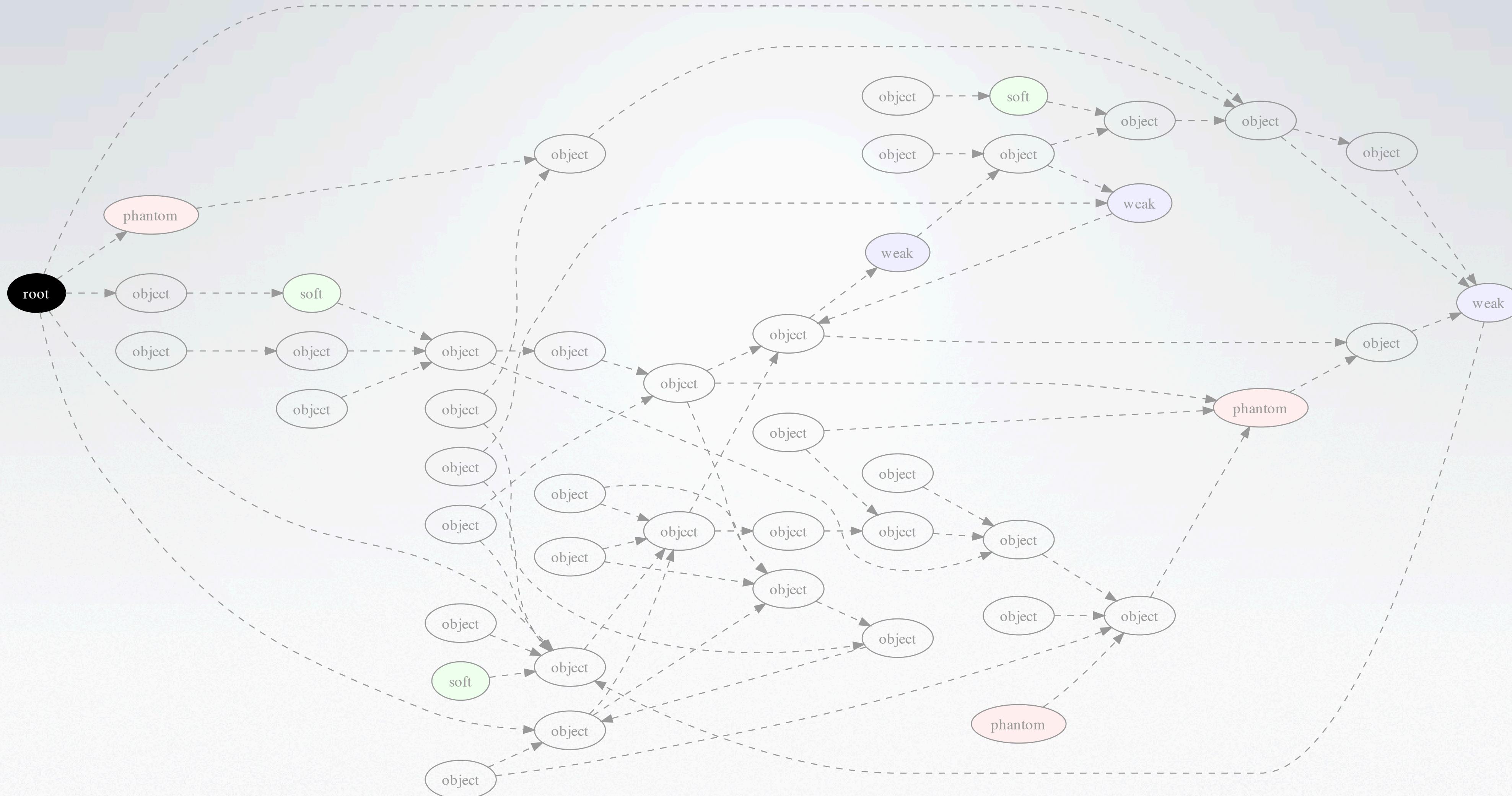
Let's mark and sweep a heap!



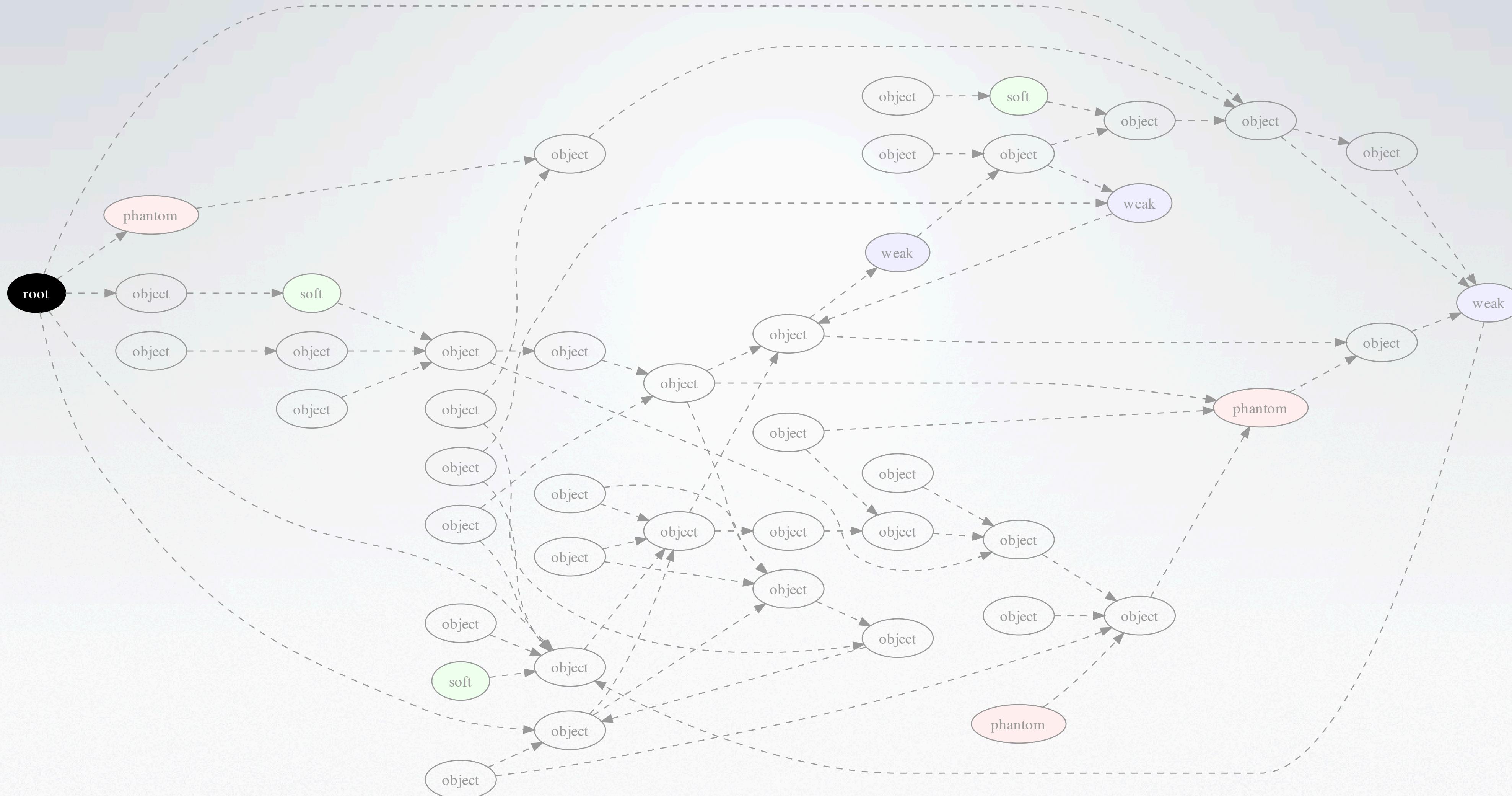
No objects are marked at first.



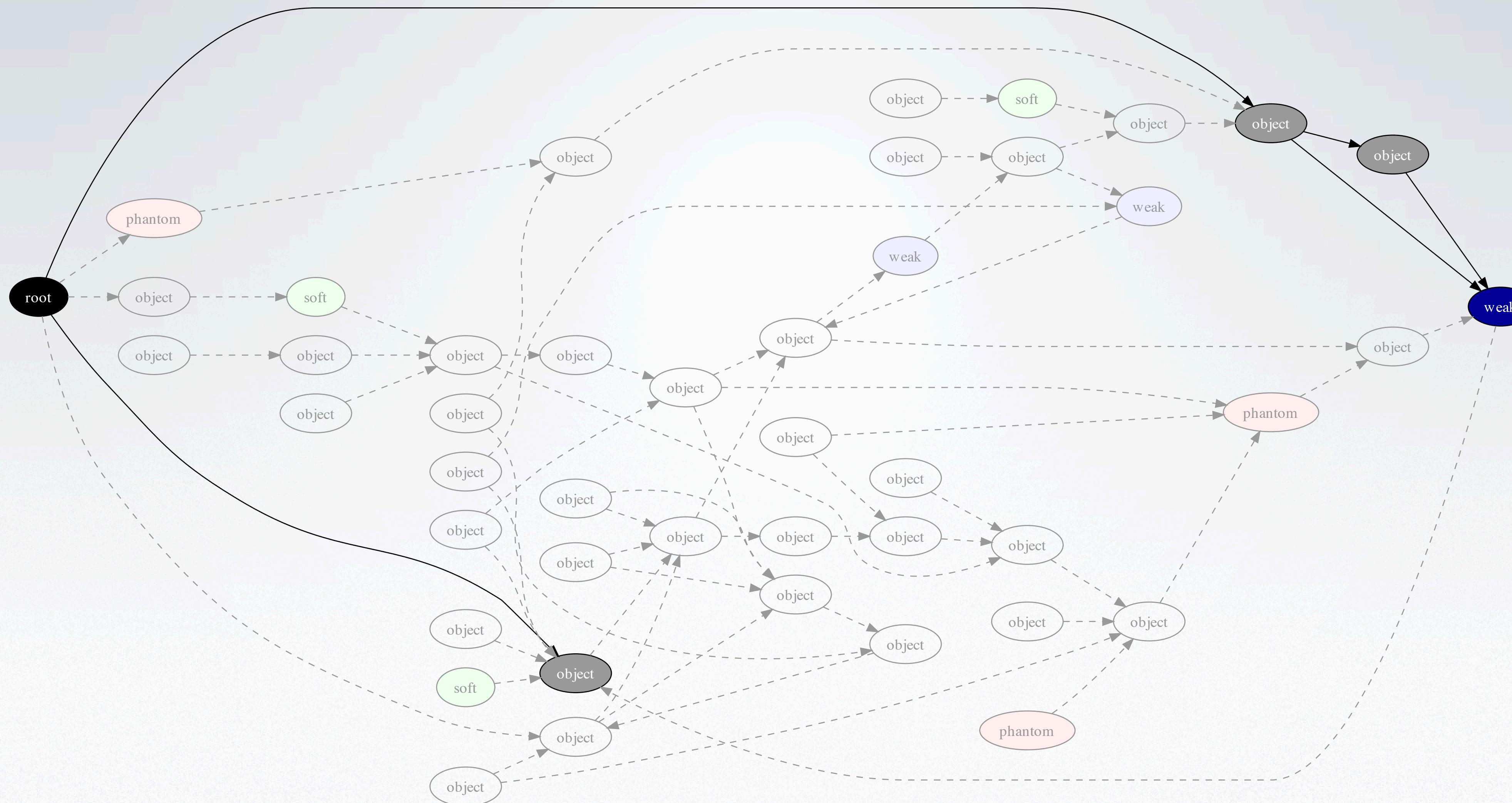
1. Start at a root.



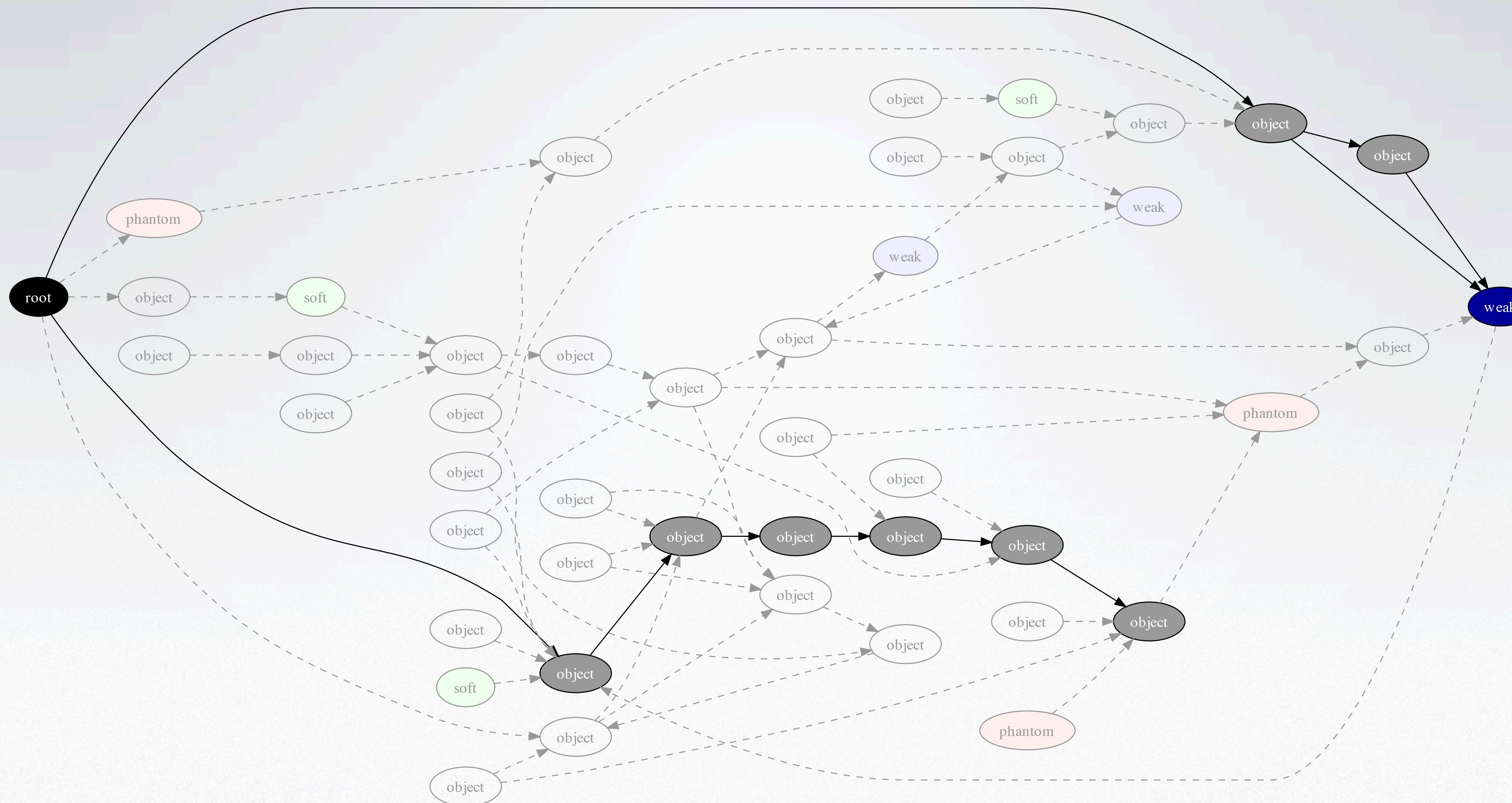
2. Trace and mark strongly-referenced objects.



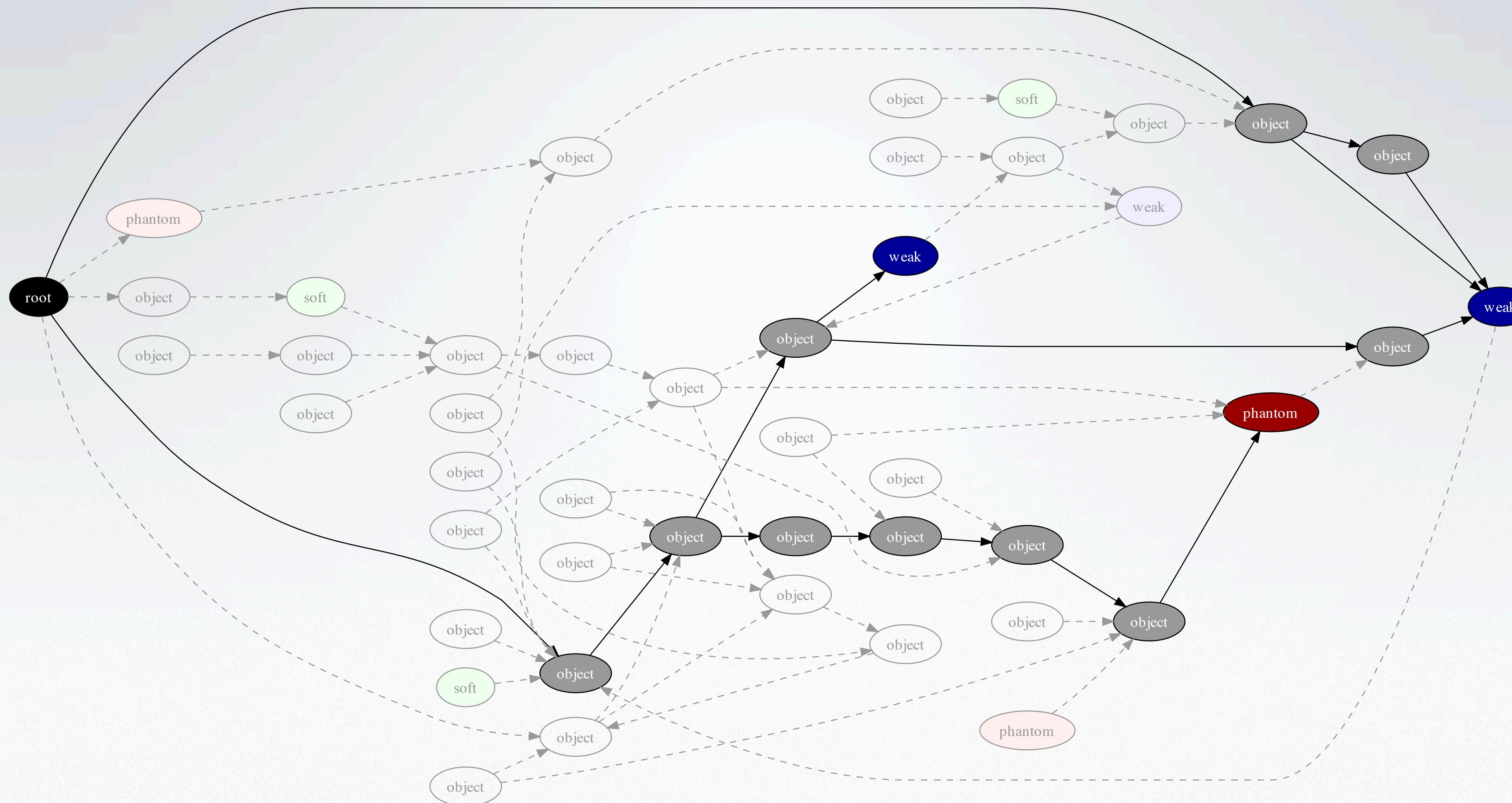
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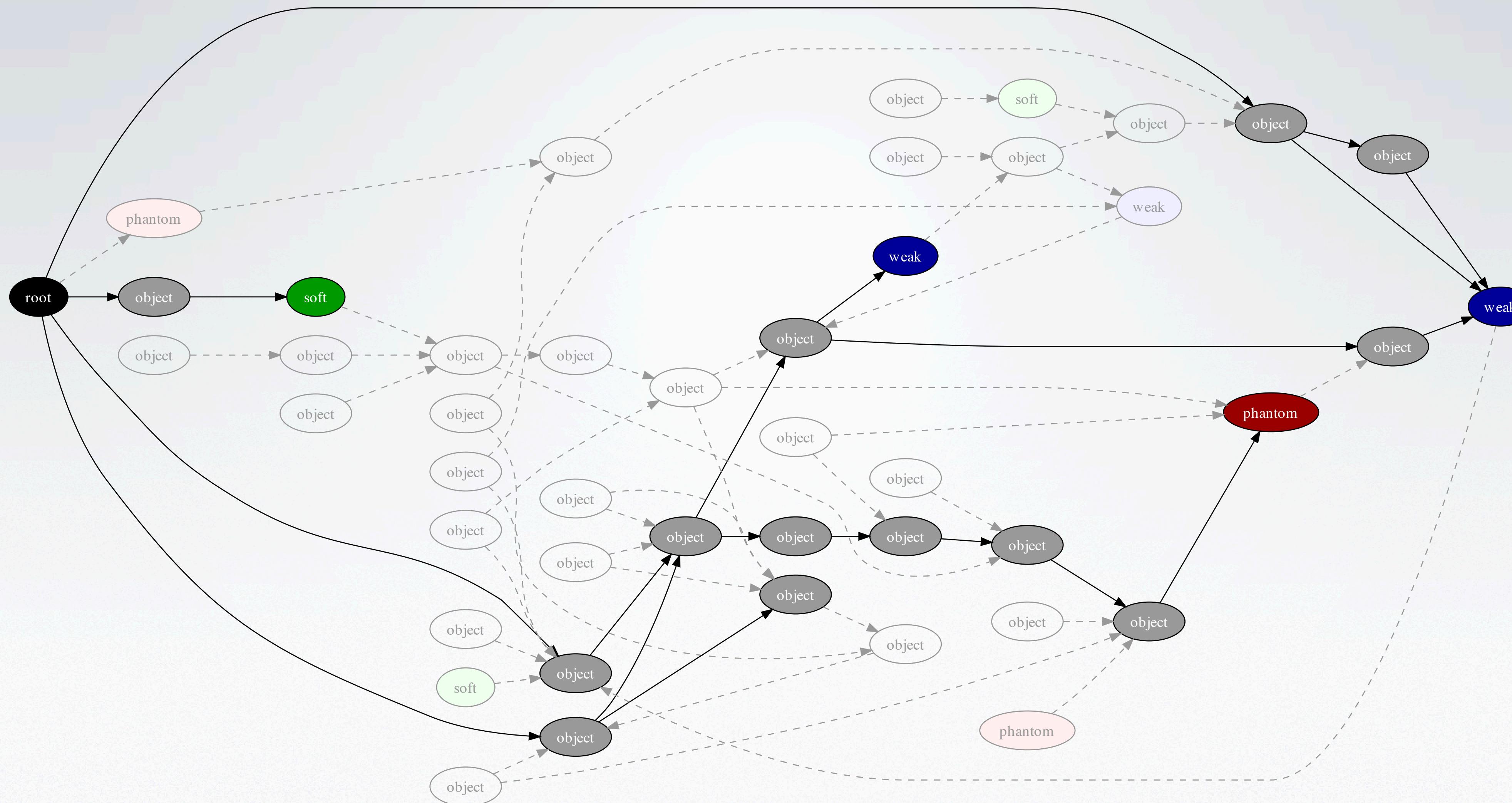
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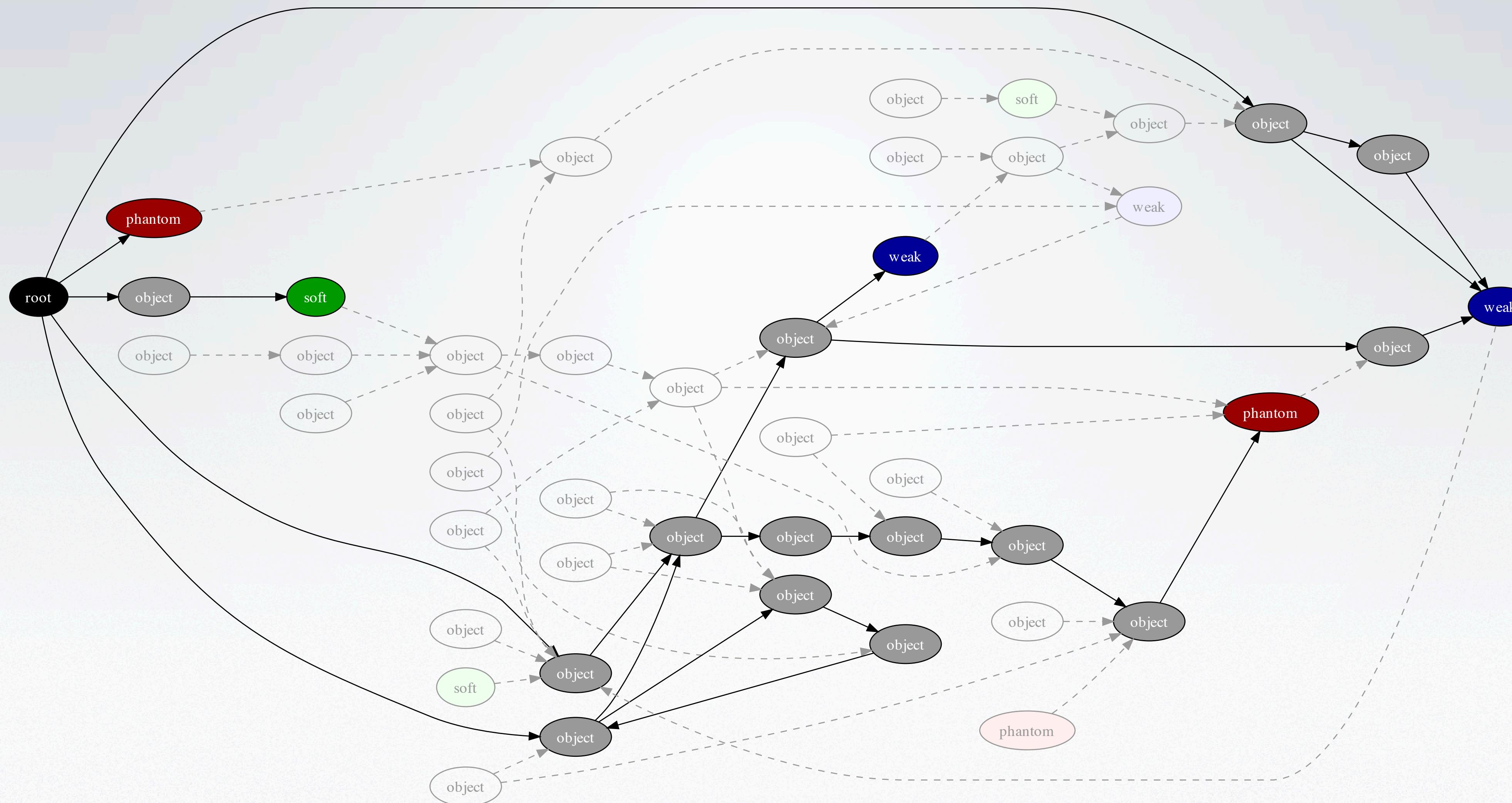
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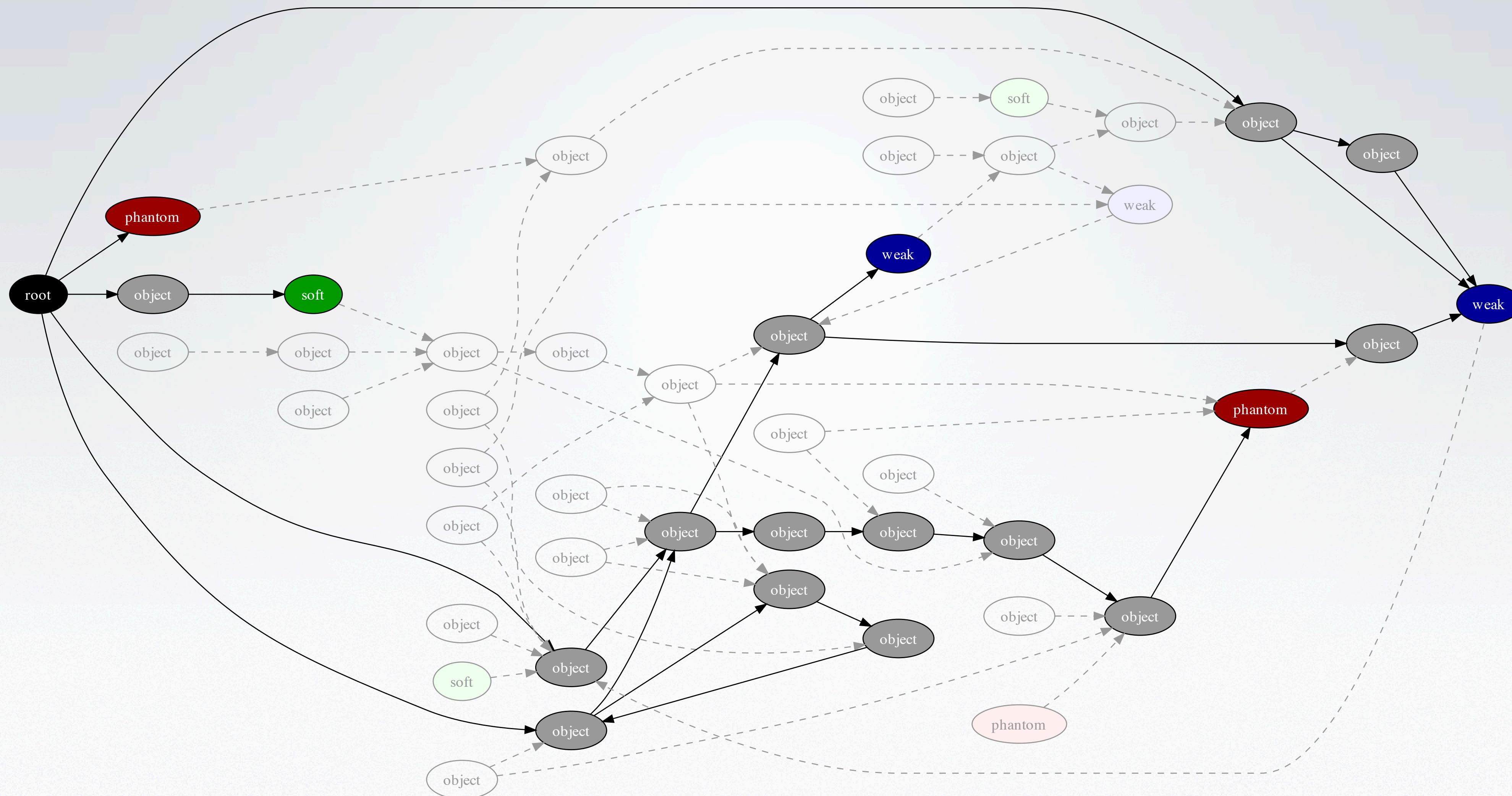
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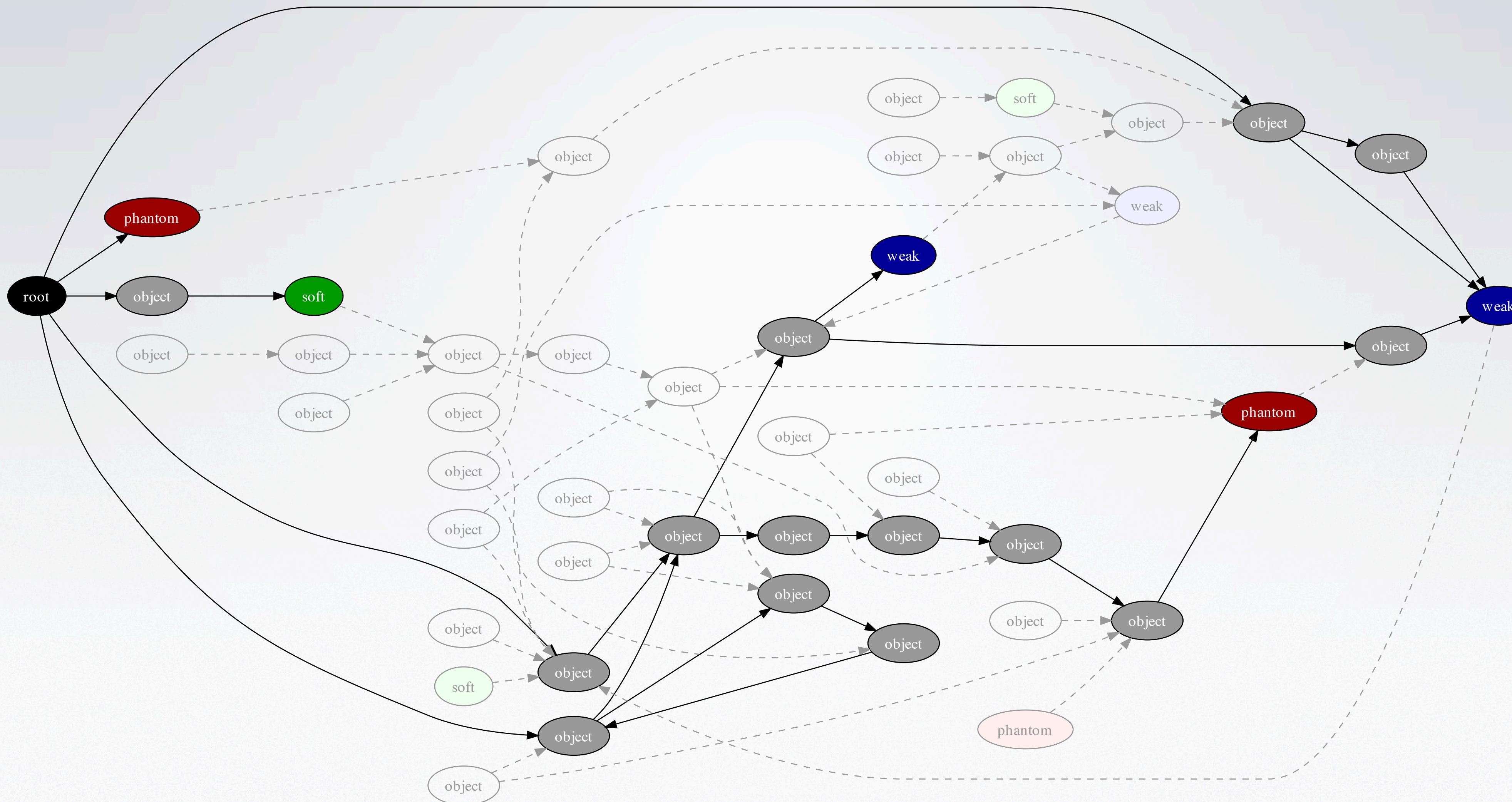
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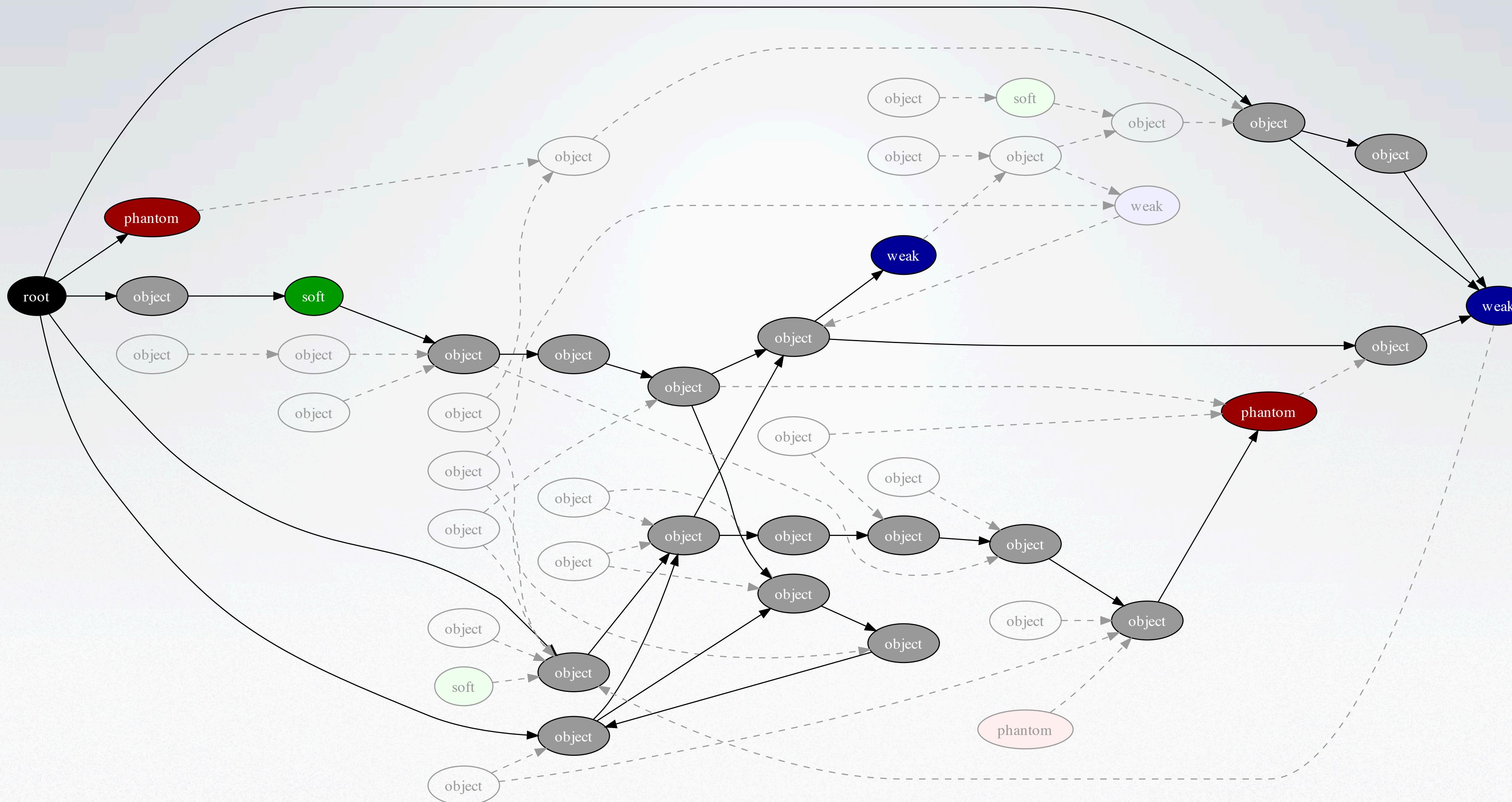
3. Optionally clear soft references.



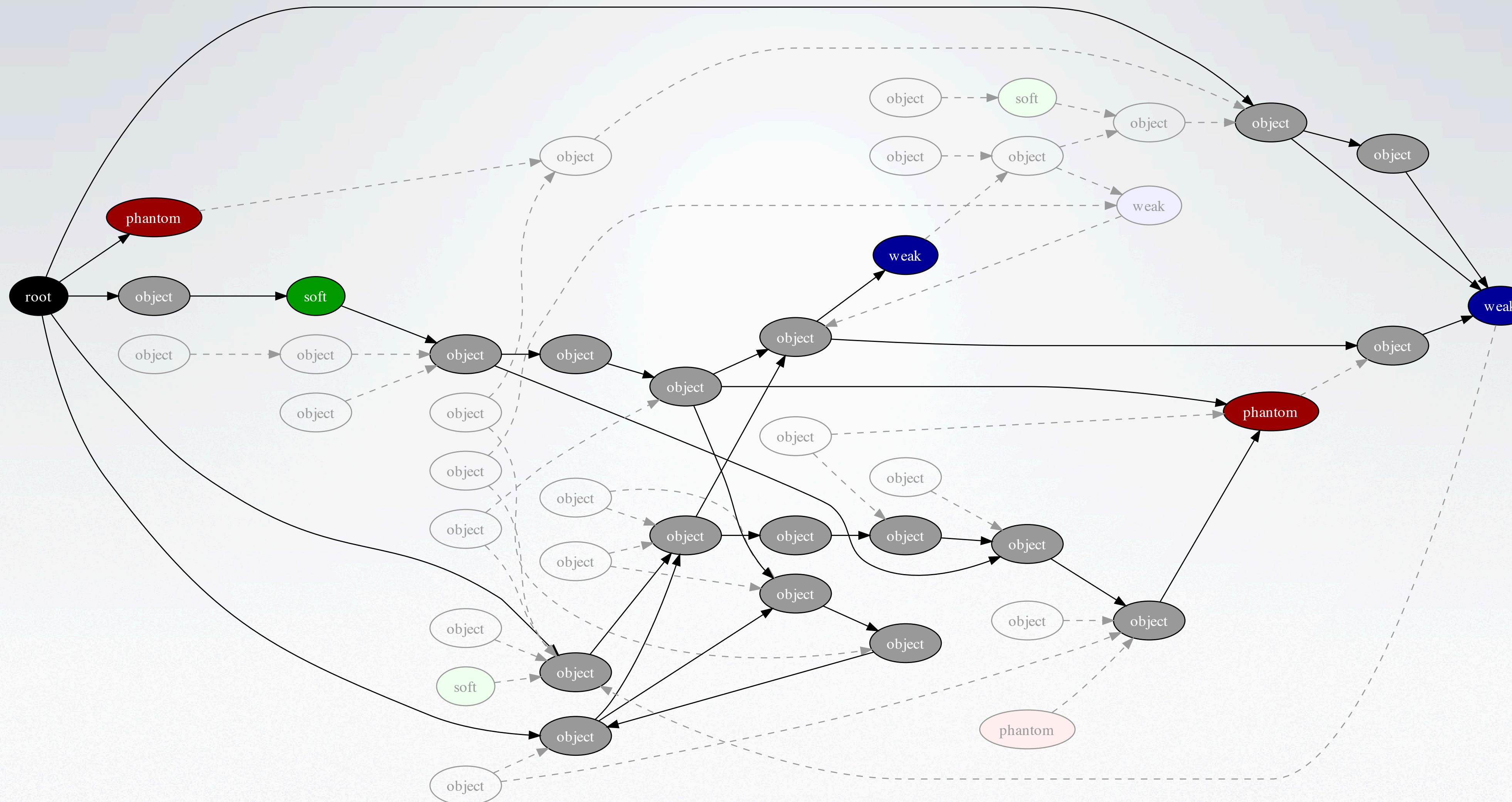
4. Trace and mark softly-referenced objects.



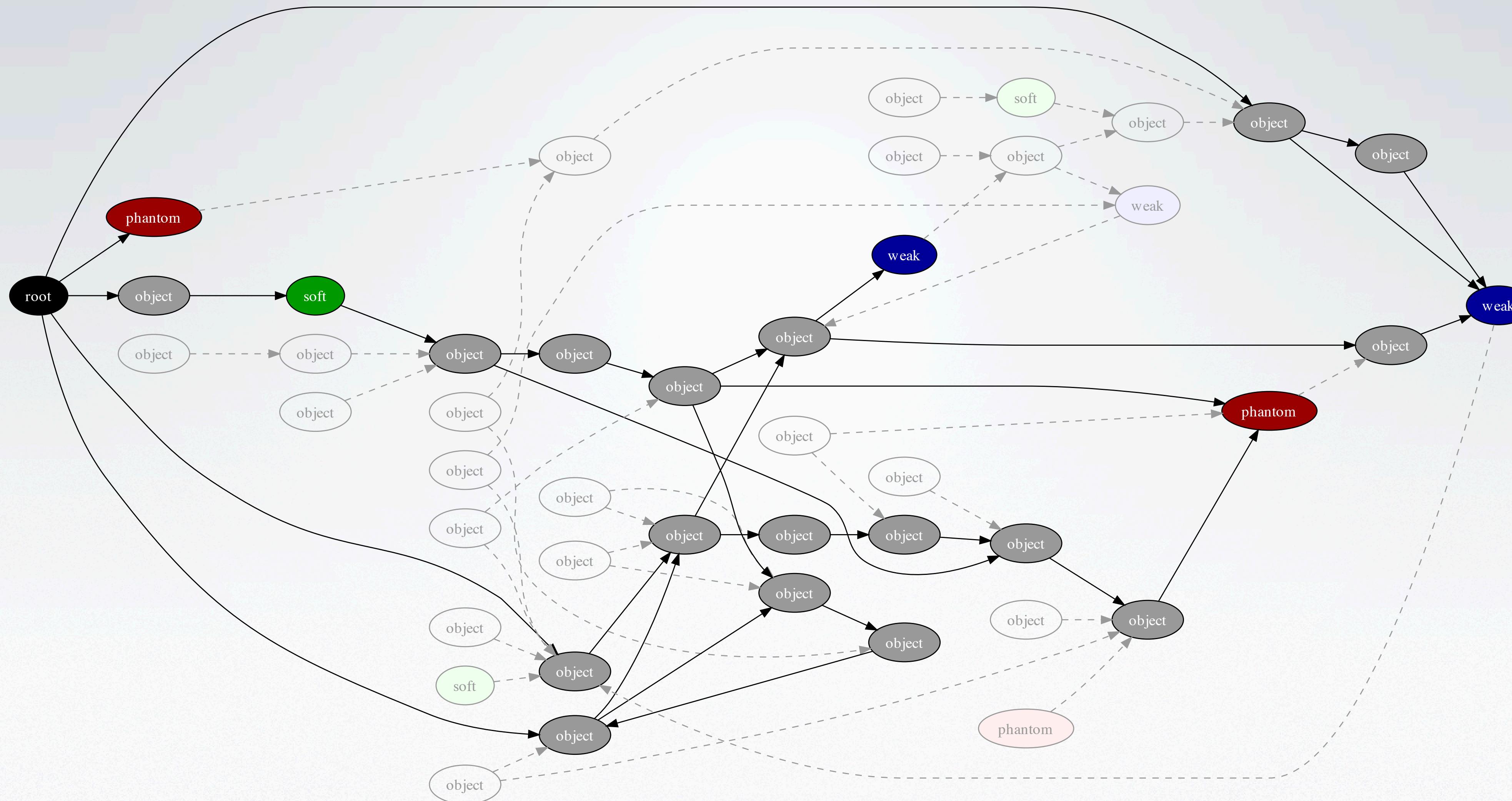
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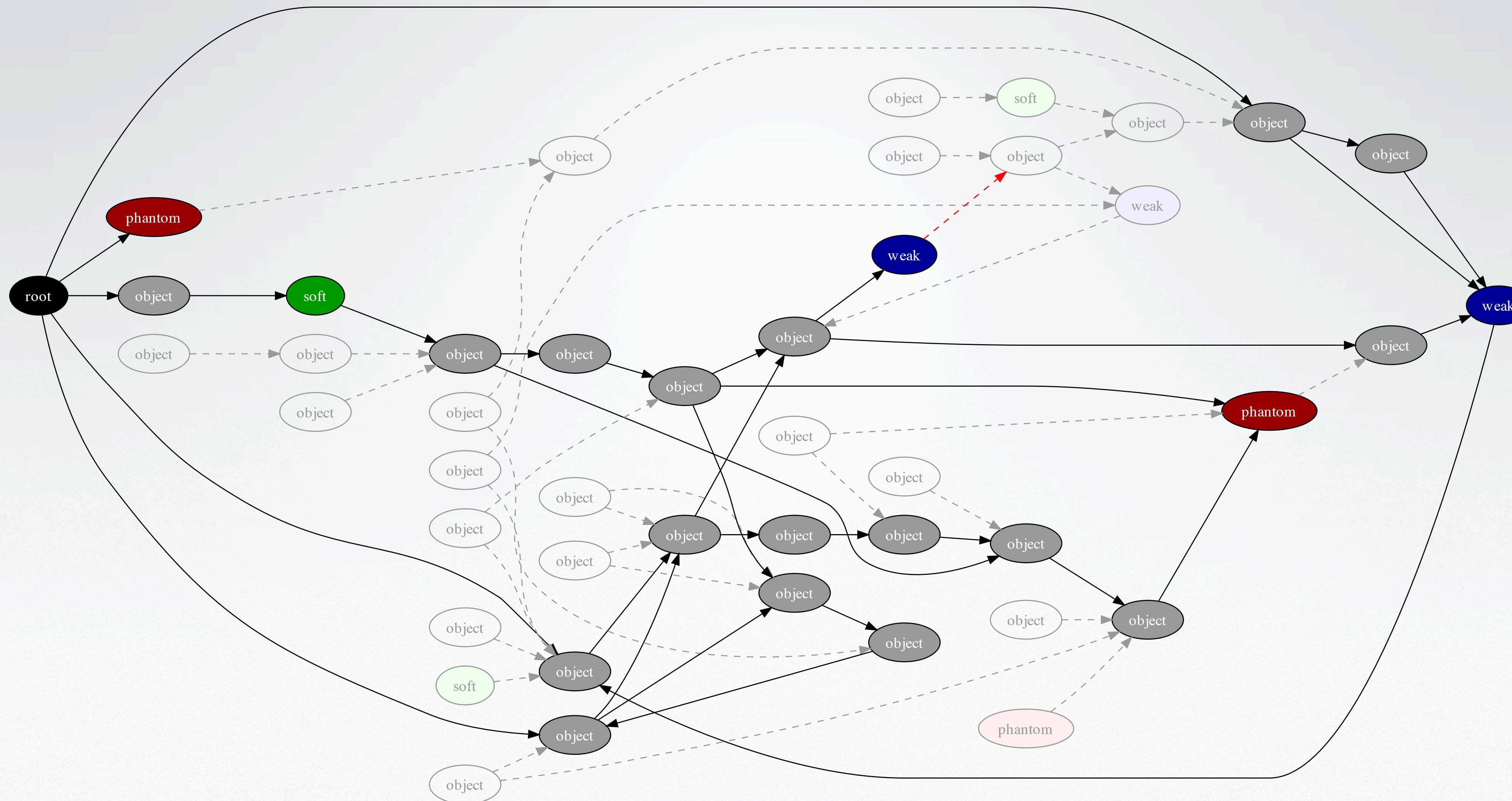
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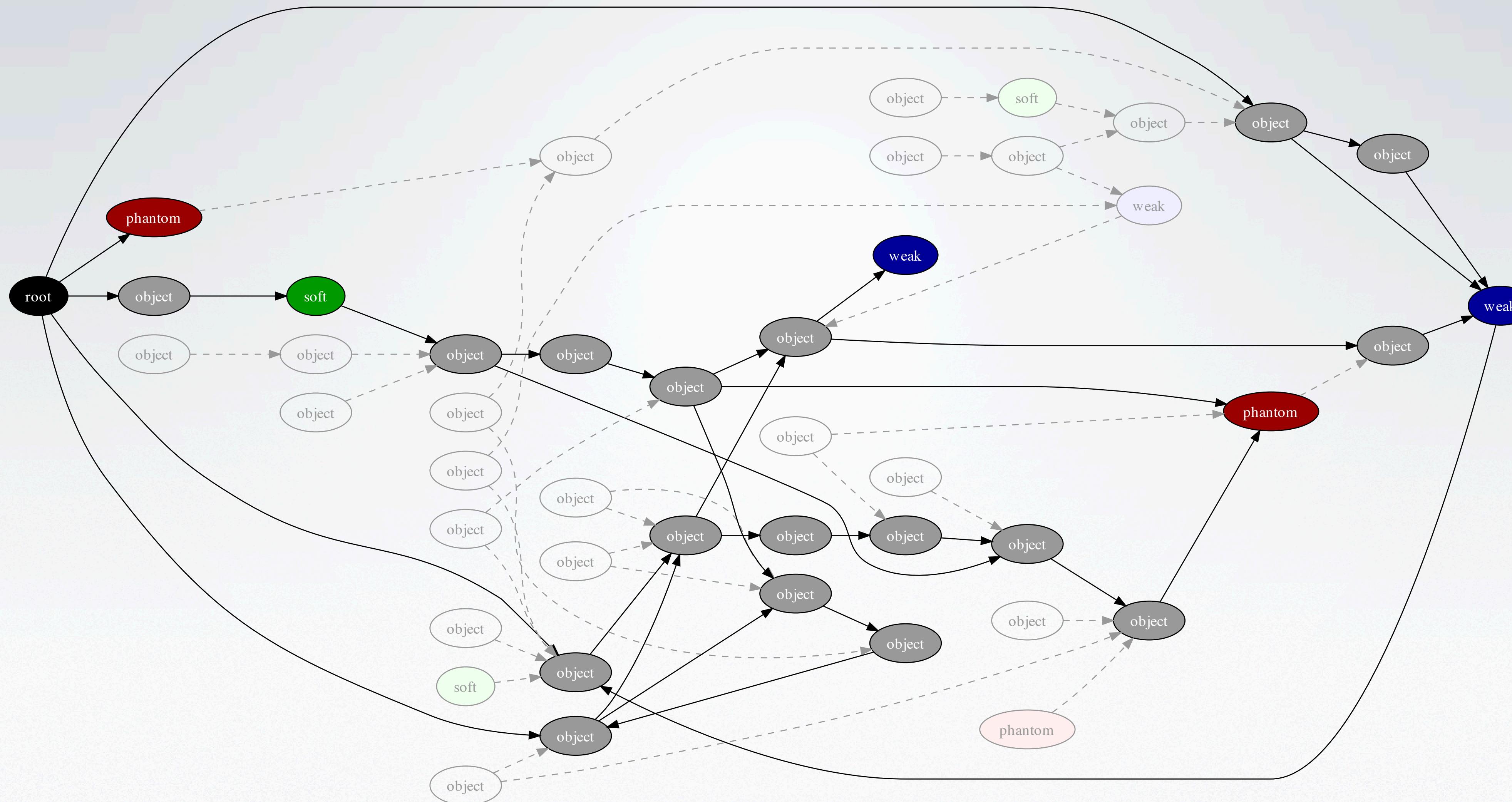
5. Clear weak references.



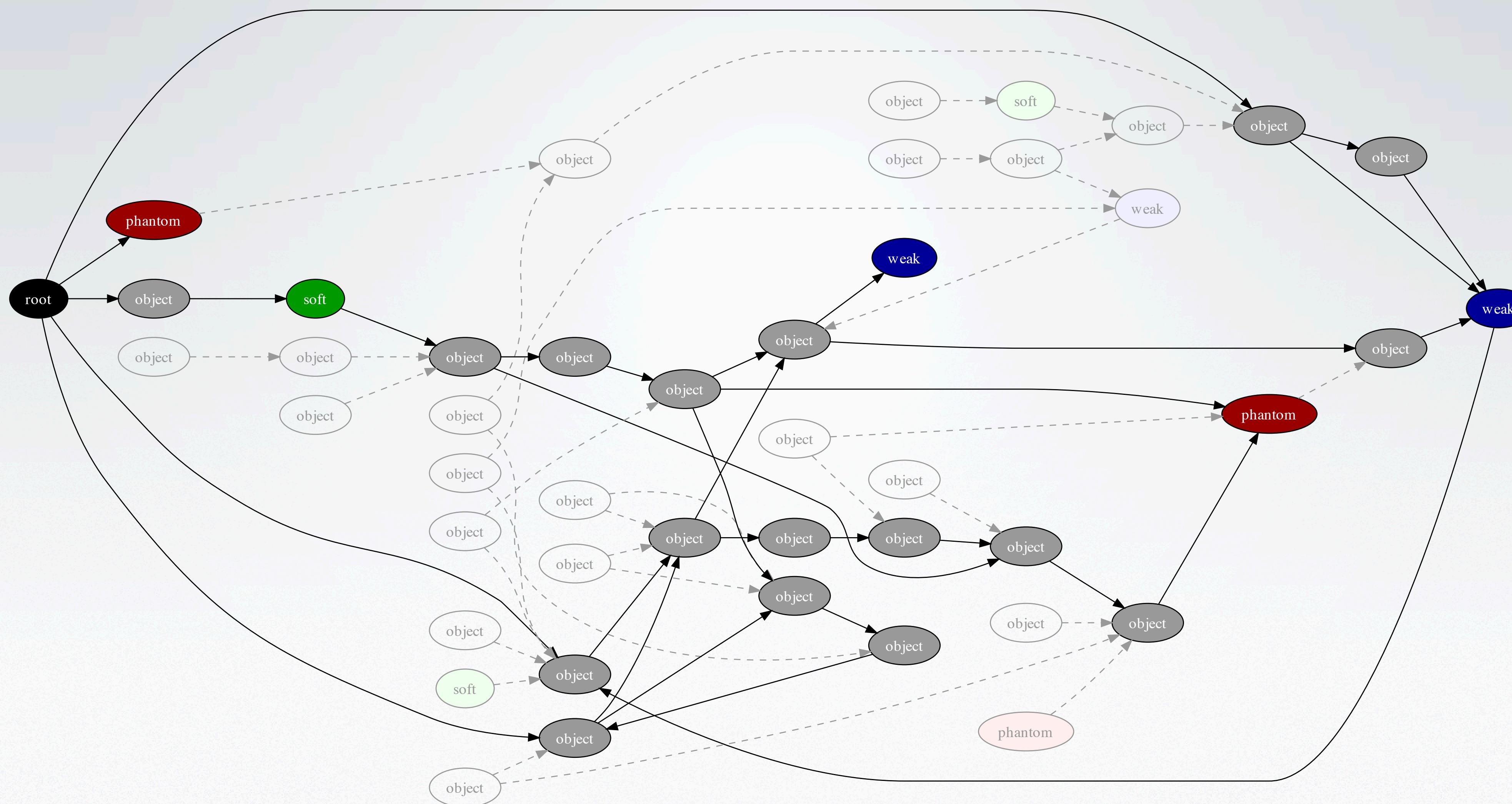
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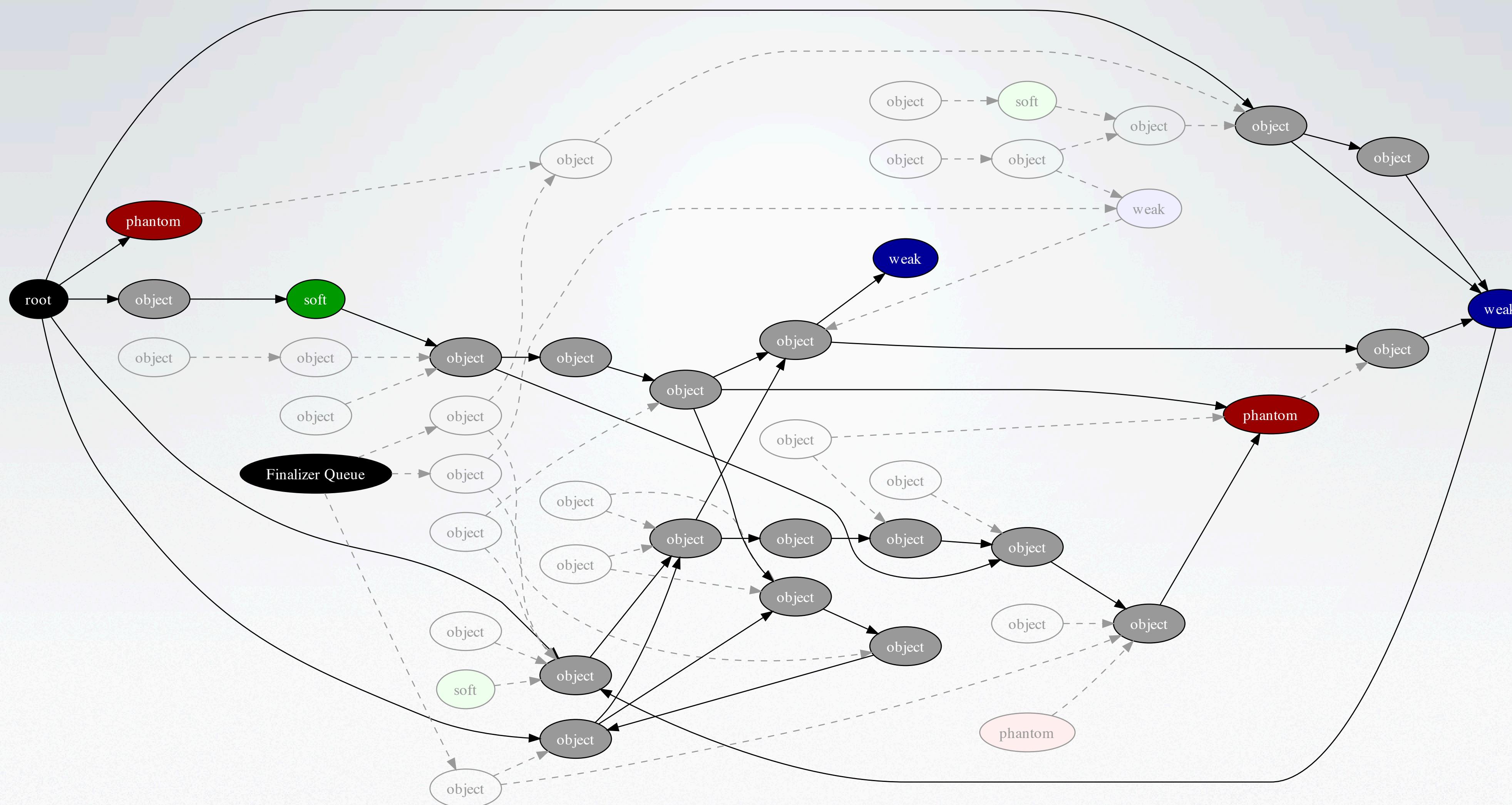
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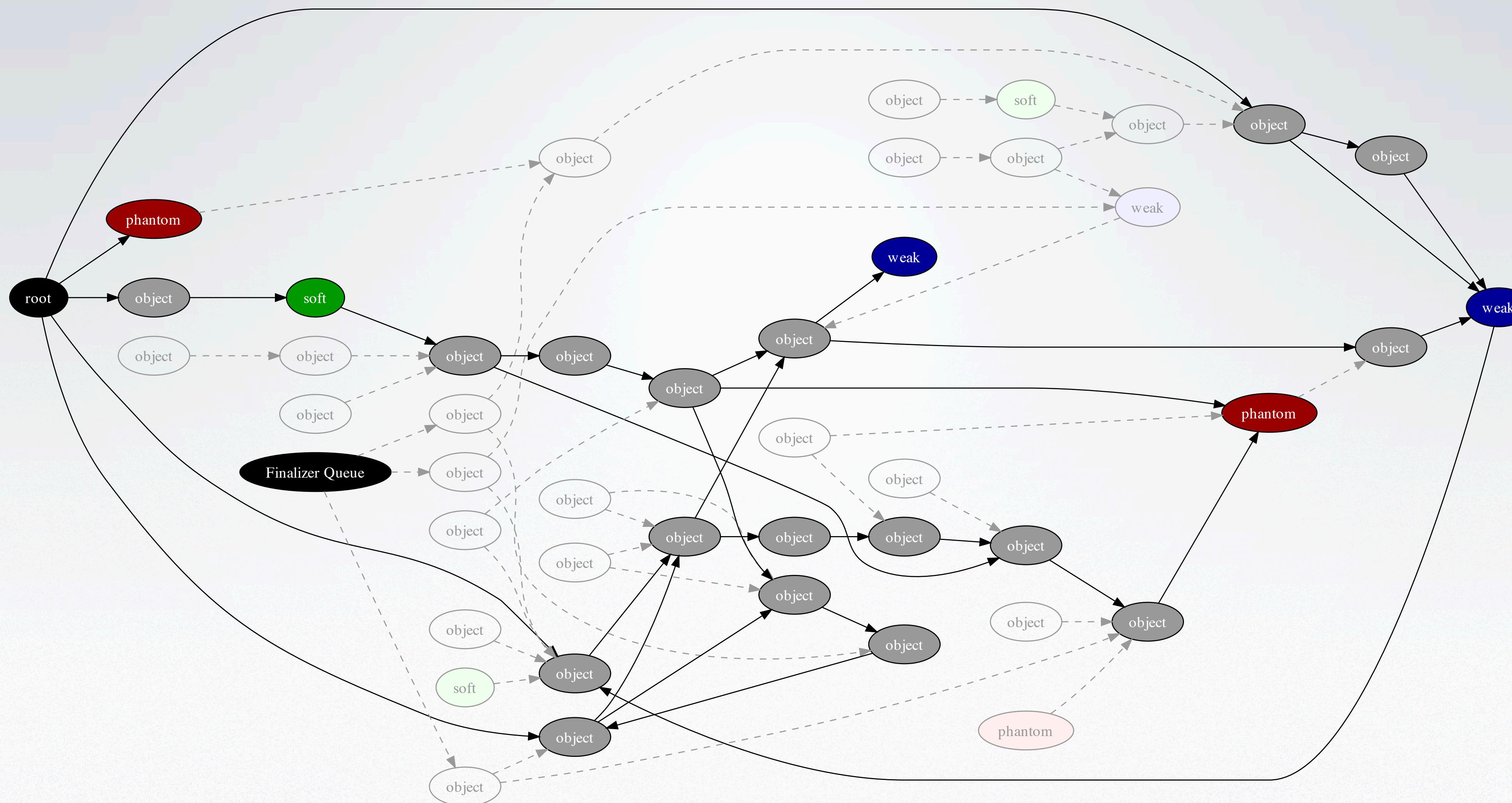
6. Enqueue finalizable objects.



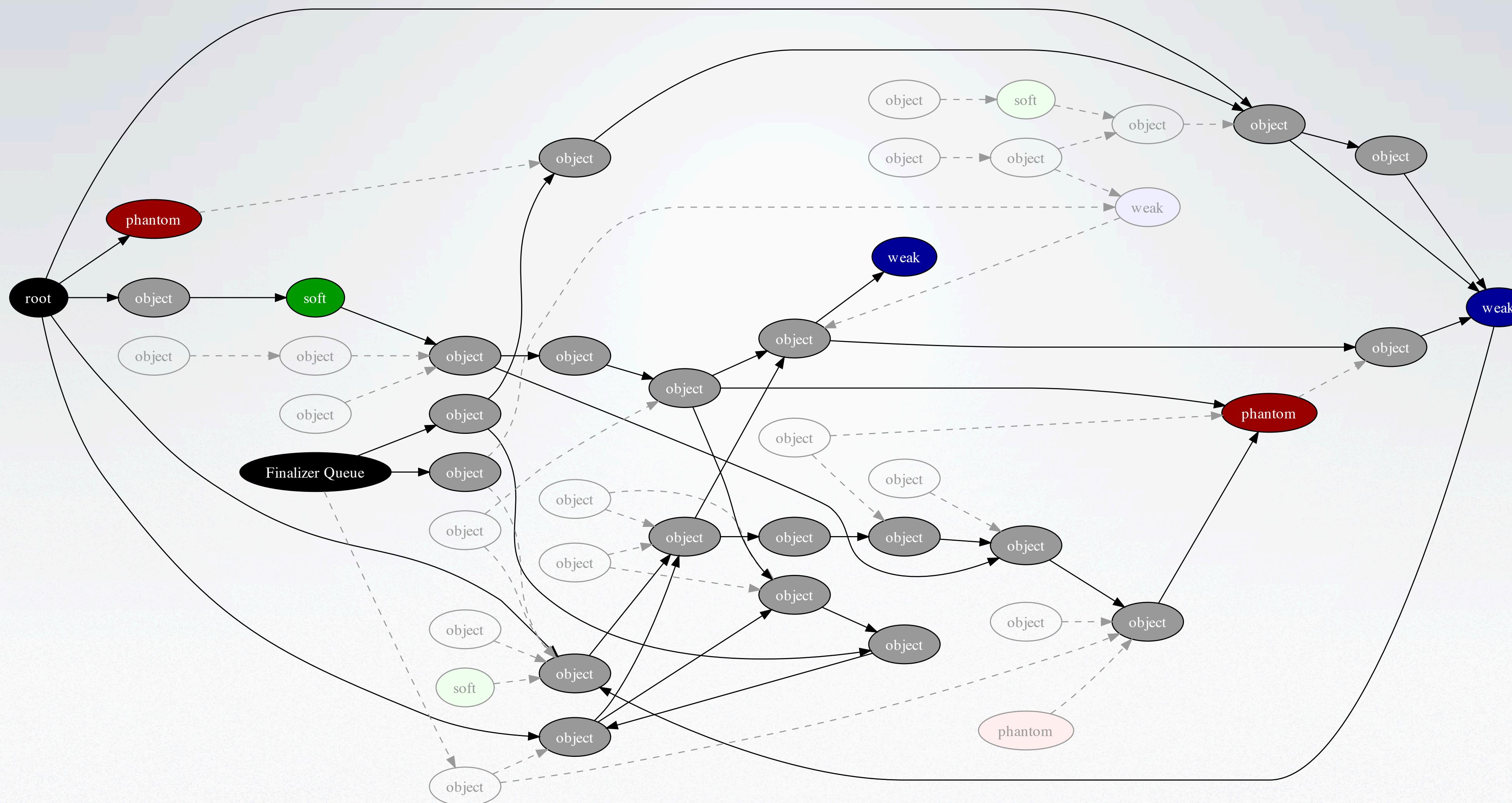
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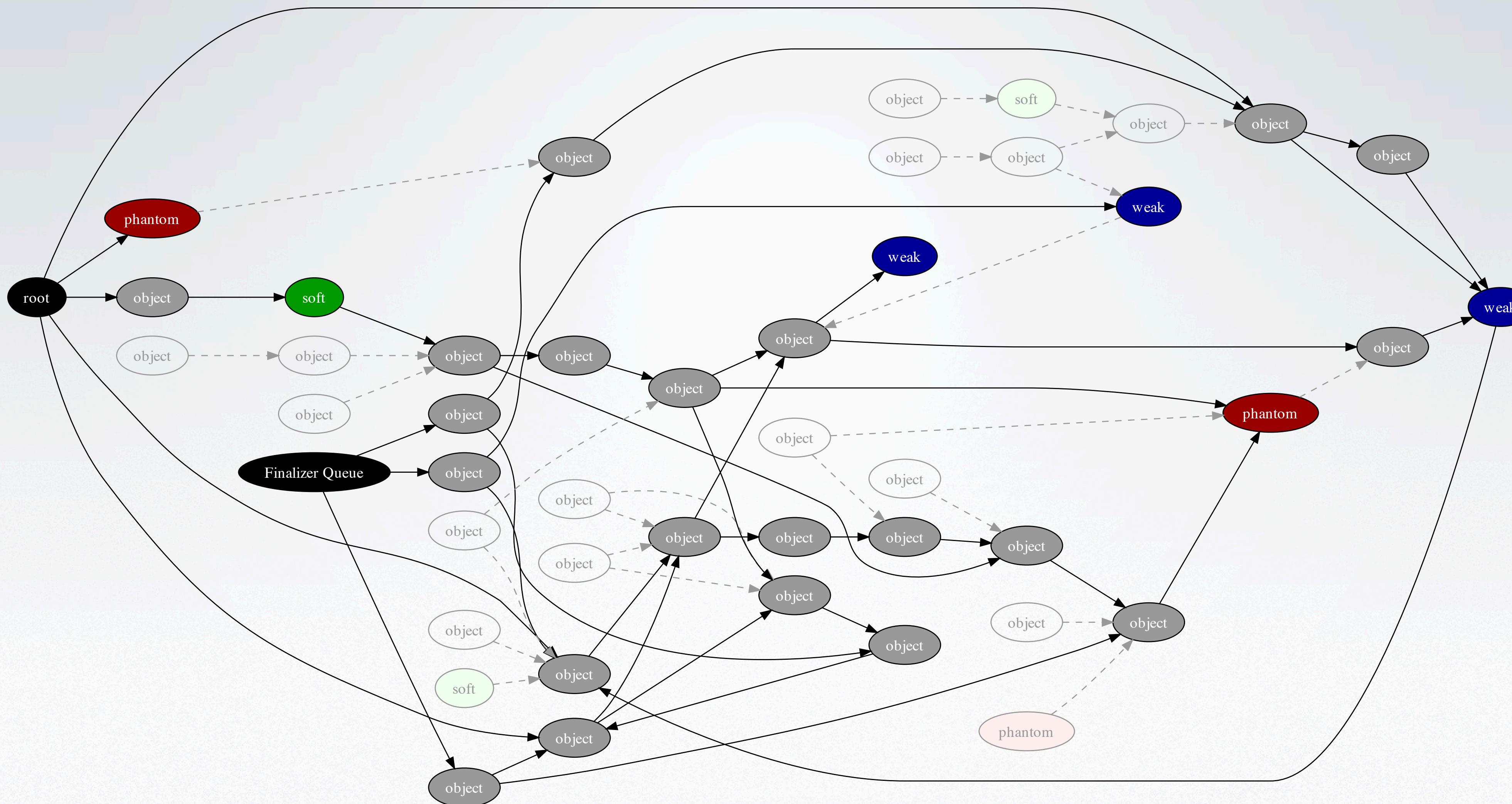
7. Repeat steps 1 through 5 for the queue.



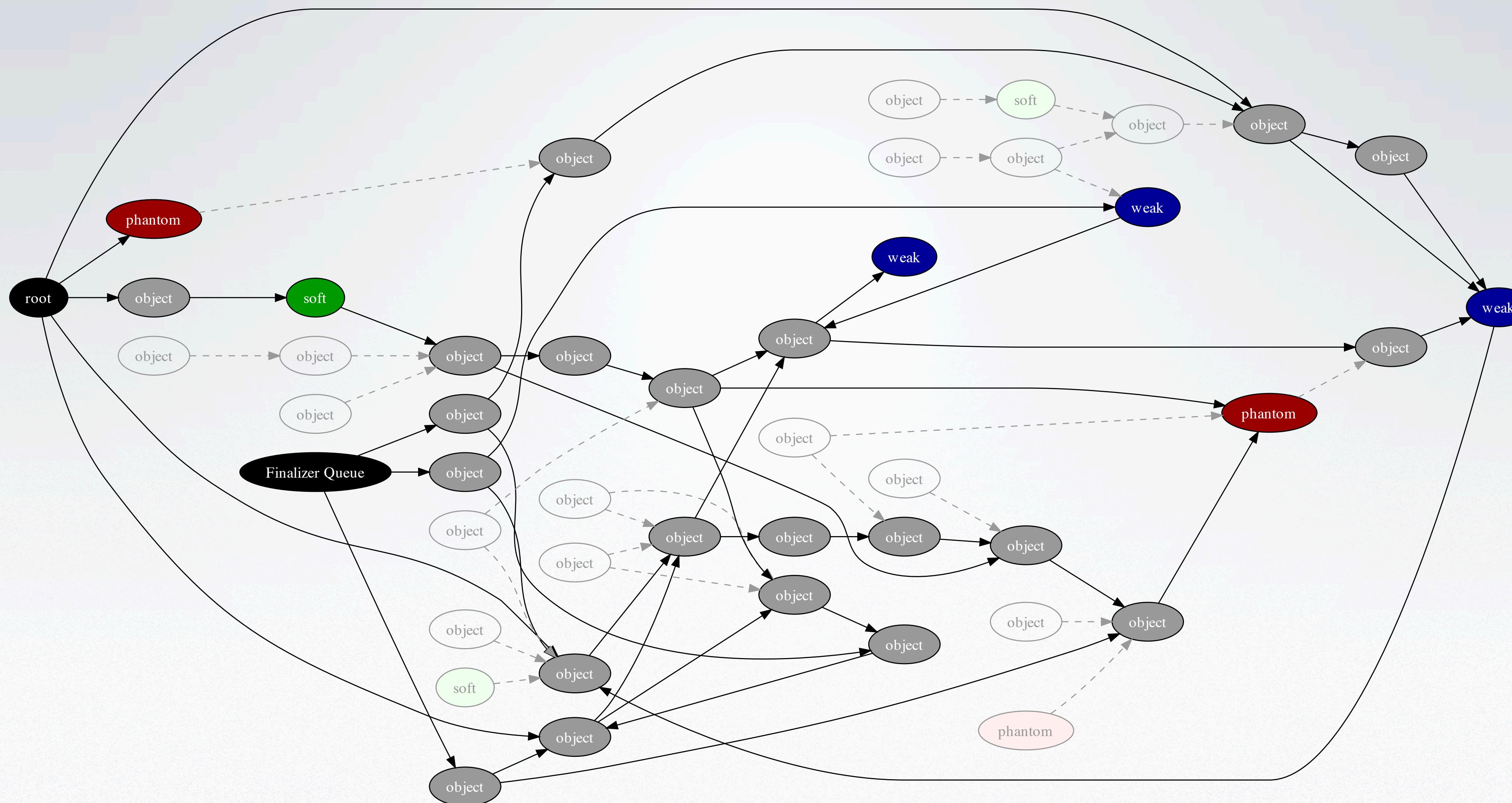
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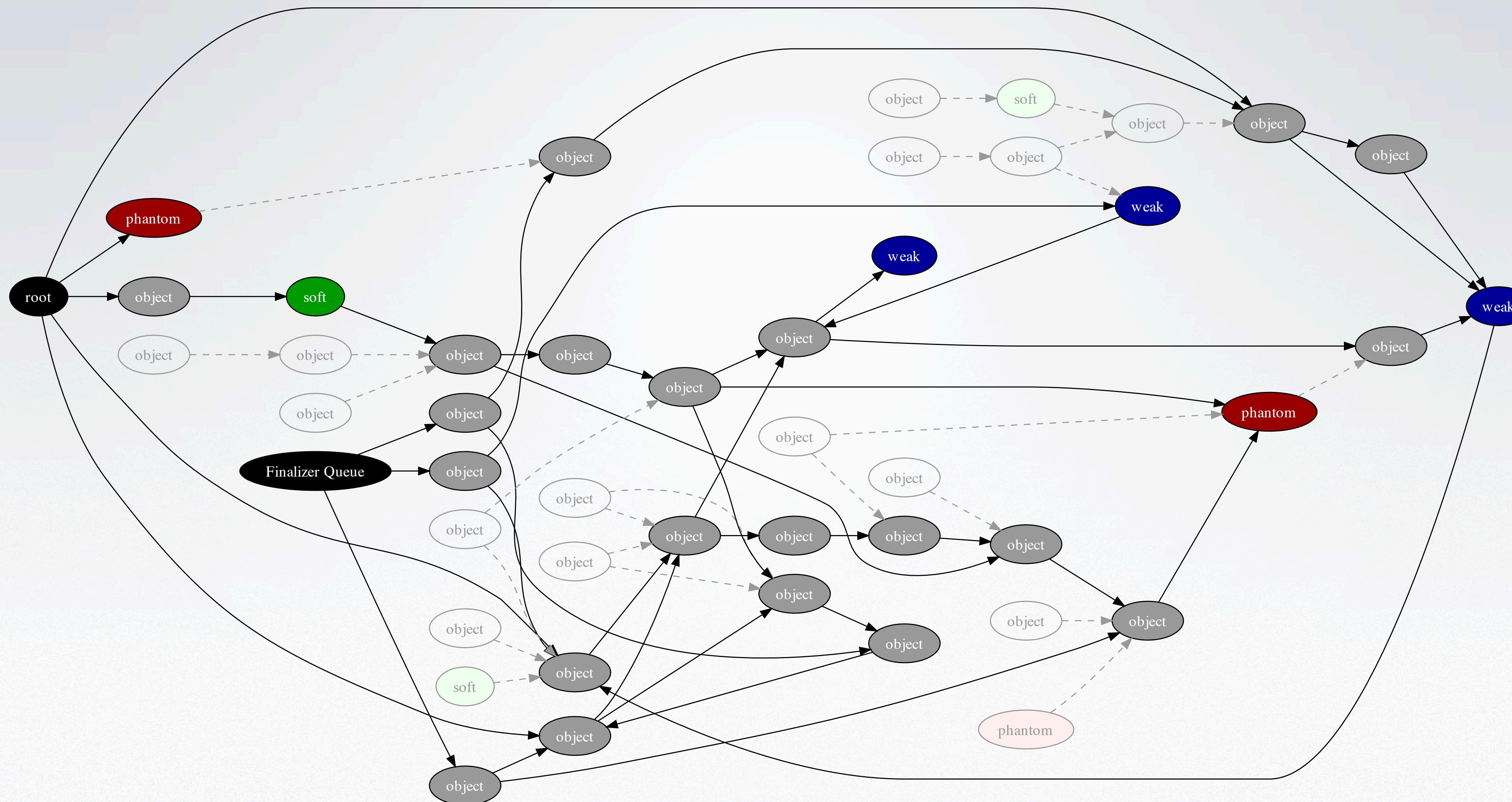
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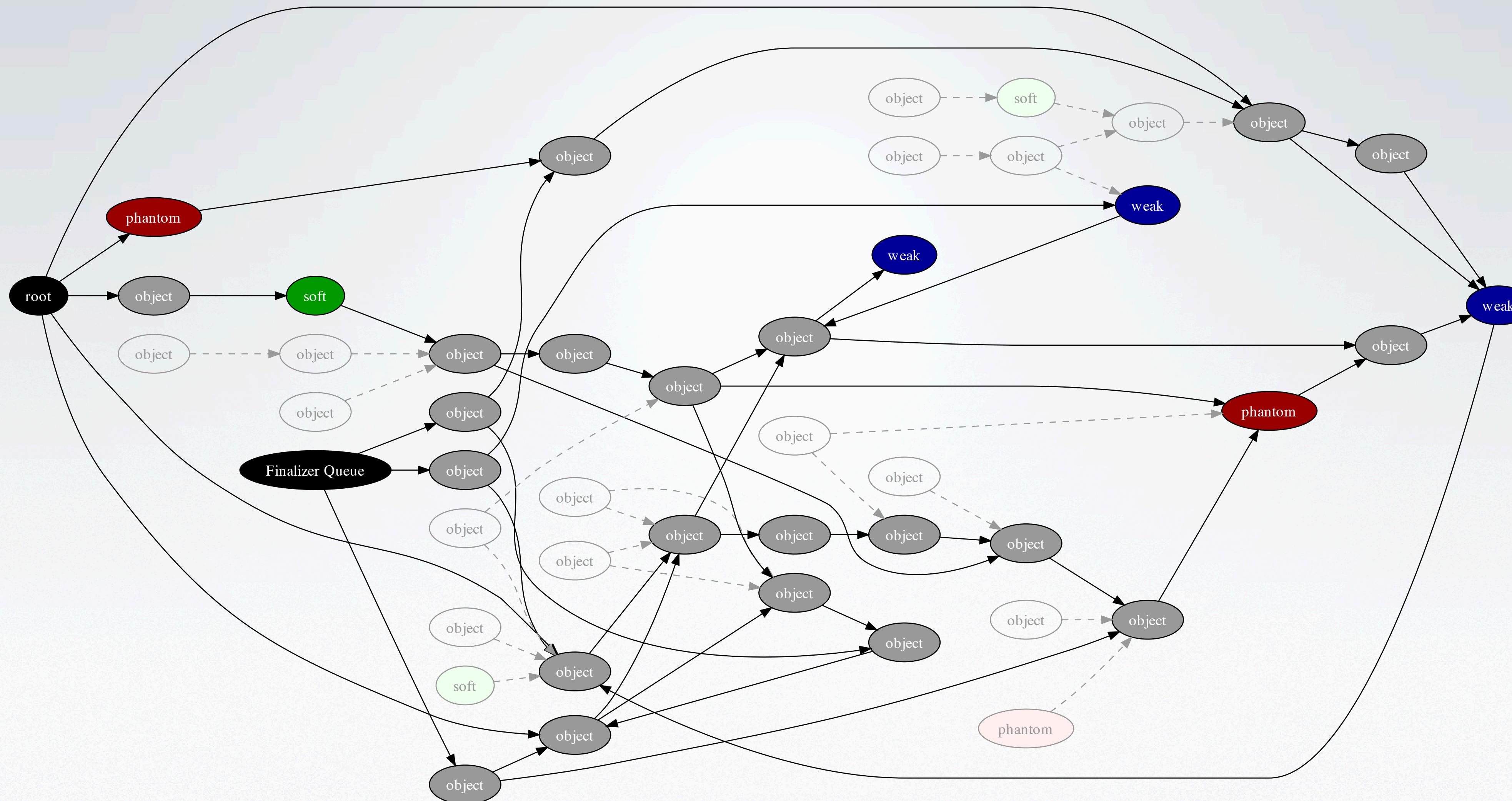
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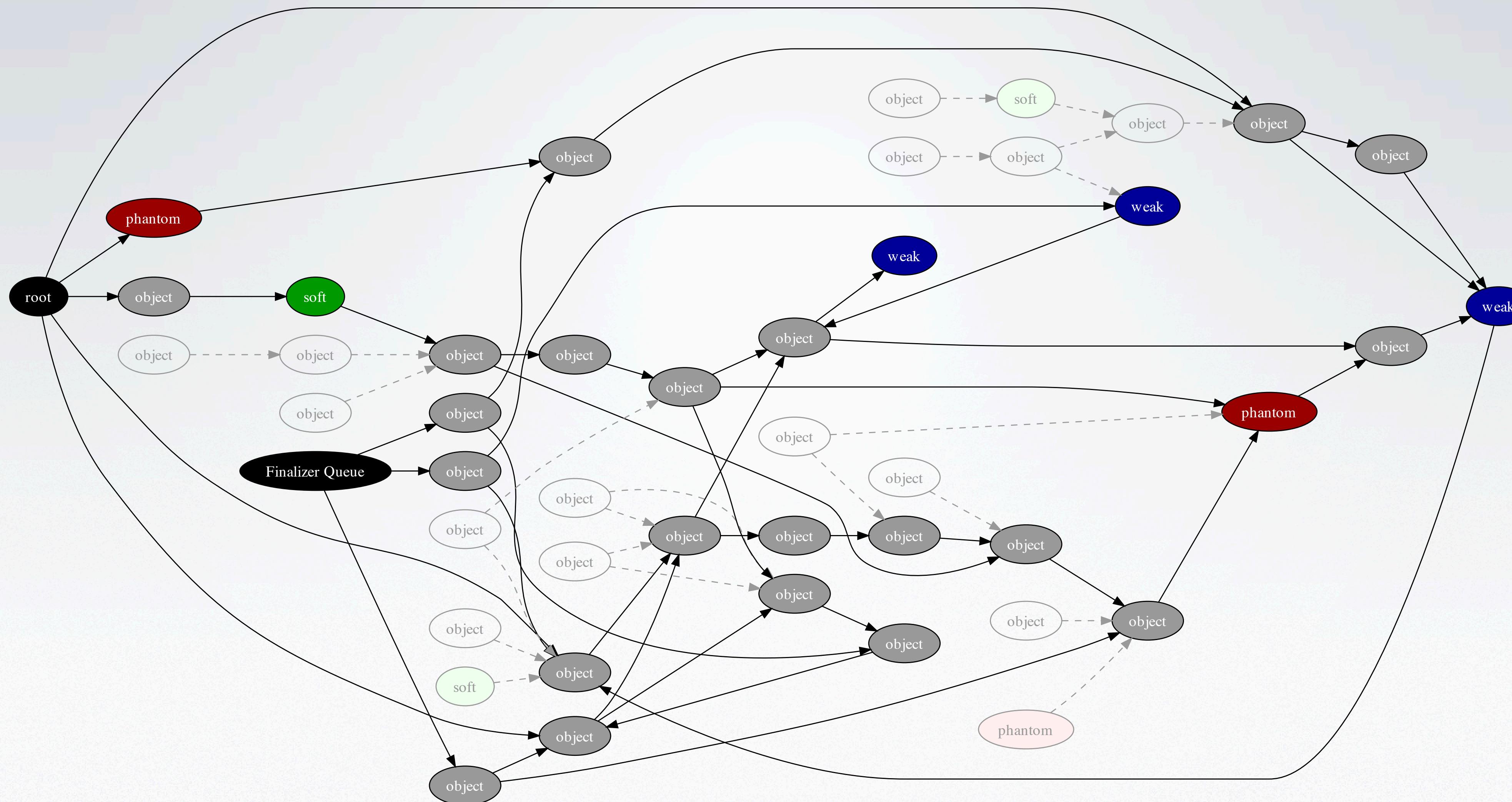
8. Possibly enqueue phantom references.



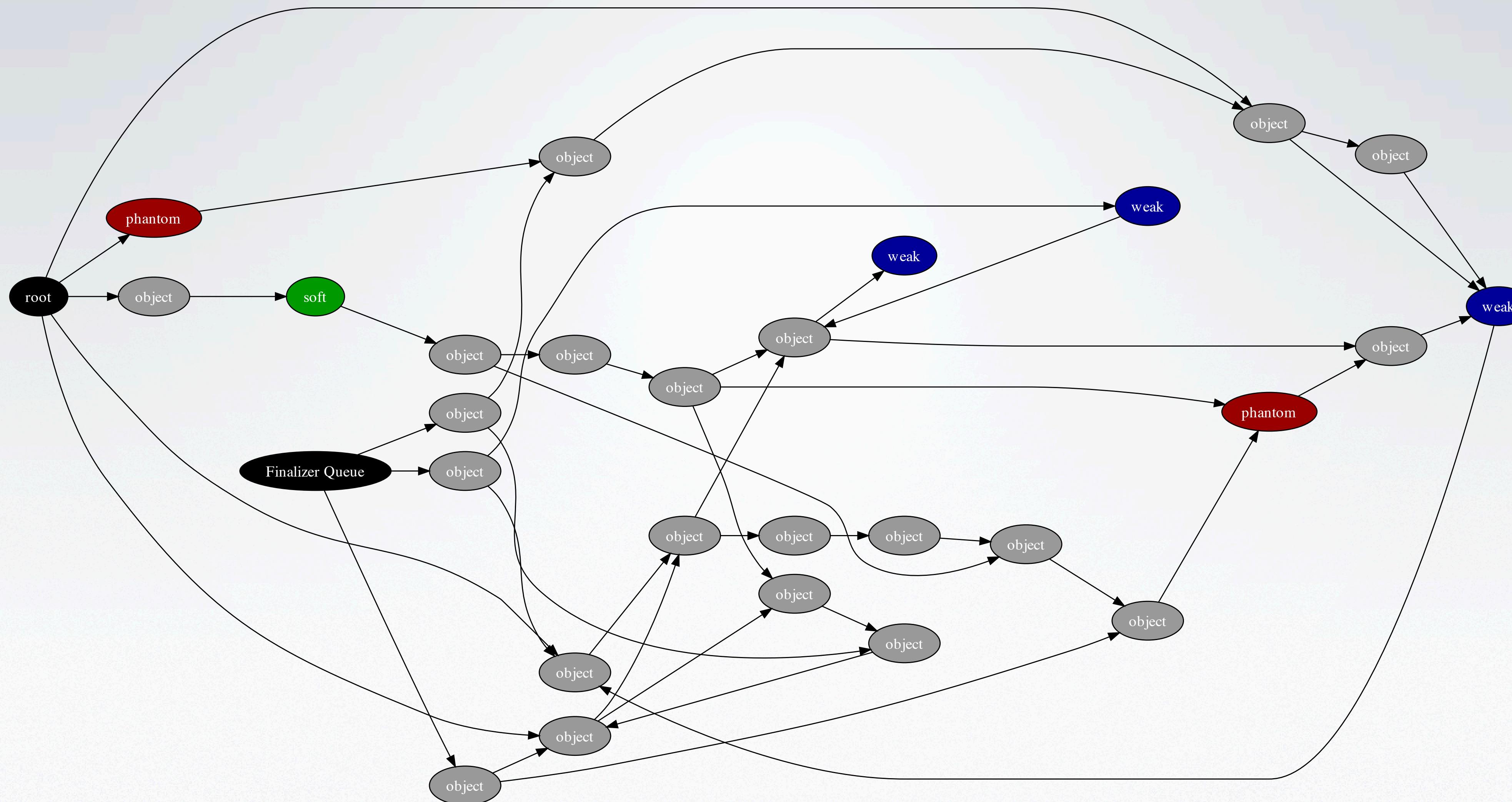
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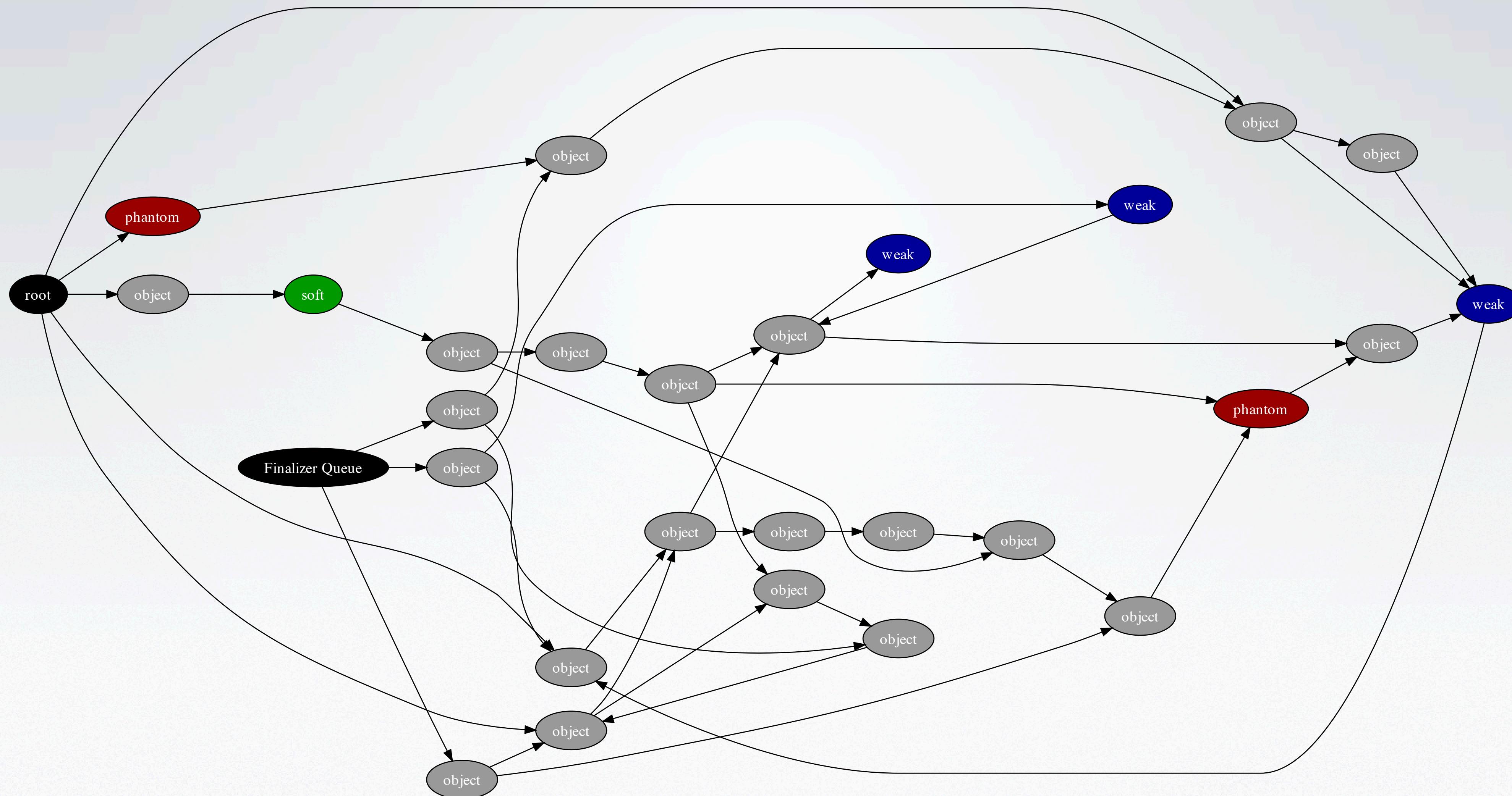
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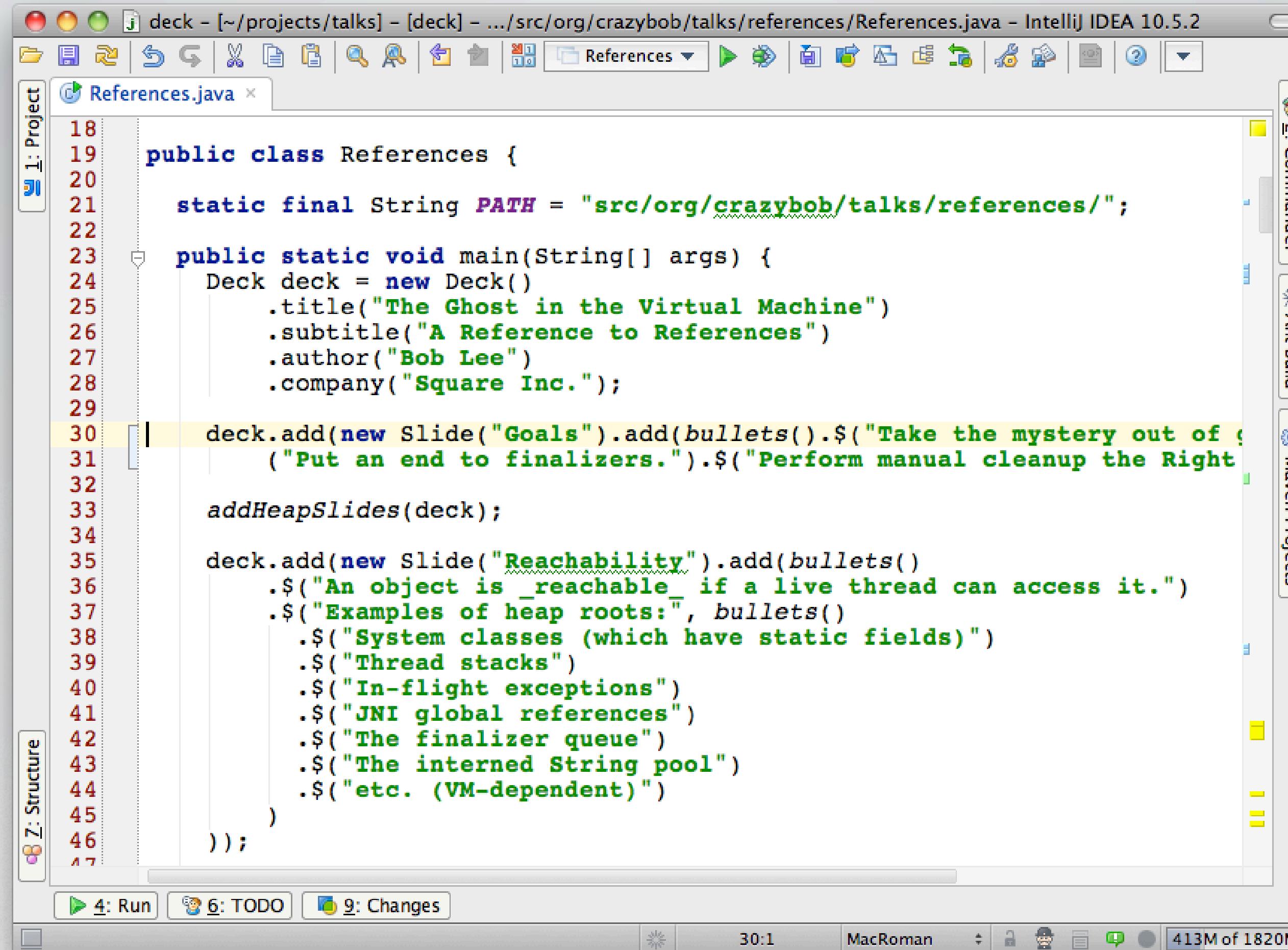
10. Repeat.



Recap

1. Start at a root.
2. Trace and mark strongly-referenced objects.
3. Optionally clear soft references.
4. Trace and mark softly-referenced objects.
5. Clear weak references.
6. Enqueue finalizable objects.
7. Repeat steps 1 through 5 for the queue.
8. Possibly enqueue phantom references.
9. The remaining objects are dead.
10. Repeat.

Brought to you by the letters J, A, V & A...



The screenshot shows the IntelliJ IDEA 10.5.2 interface with the file `References.java` open. The code implements a `Deck` class for generating presentation slides, specifically for a talk titled "The Ghost in the Virtual Machine". The `main` method creates a `Deck` instance and adds several slides. The first slide is a `Goals` slide with bullet points about memory management. The second slide is a `Reachability` slide listing various types of heap roots.

```
18  public class References {
19
20      static final String PATH = "src/org/crazybob/talks/references/";
21
22      public static void main(String[] args) {
23          Deck deck = new Deck()
24              .title("The Ghost in the Virtual Machine")
25              .subtitle("A Reference to References")
26              .author("Bob Lee")
27              .company("Square Inc.");
28
29          deck.add(new Slide("Goals").add(bullets().$("Take the mystery out of Garbage Collection")
30                           .$("Put an end to finalizers.").$("Perform manual cleanup the Right Way"))
31                  .addHeapSlides(deck));
32
33          deck.add(new Slide("Reachability").add(bullets())
34              .$("An object is _reachable_ if a live thread can access it.")
35              .$("Examples of heap roots:", bullets()
36                  .$("System classes (which have static fields)")
37                  .$("Thread stacks")
38                  .$("In-flight exceptions")
39                  .$("JNI global references")
40                  .$("The finalizer queue")
41                  .$("The interned String pool")
42                  .$("etc. (VM-dependent)"))
43
44      );
45
46  });
47
```

Thank You!

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