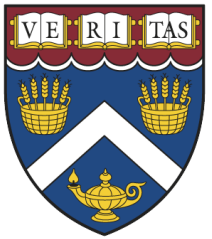
In the Last Week

- Some questions around the final project
  - What's going on with the GC footprint?
  - What are the parameters to `onPointerCreate`?
- Final exam logistics
  - Class tonight and next Monday
  - Final exam released early morning on the 15th
  - Exam due at midnight on the 19th
  - No late days for the final exam

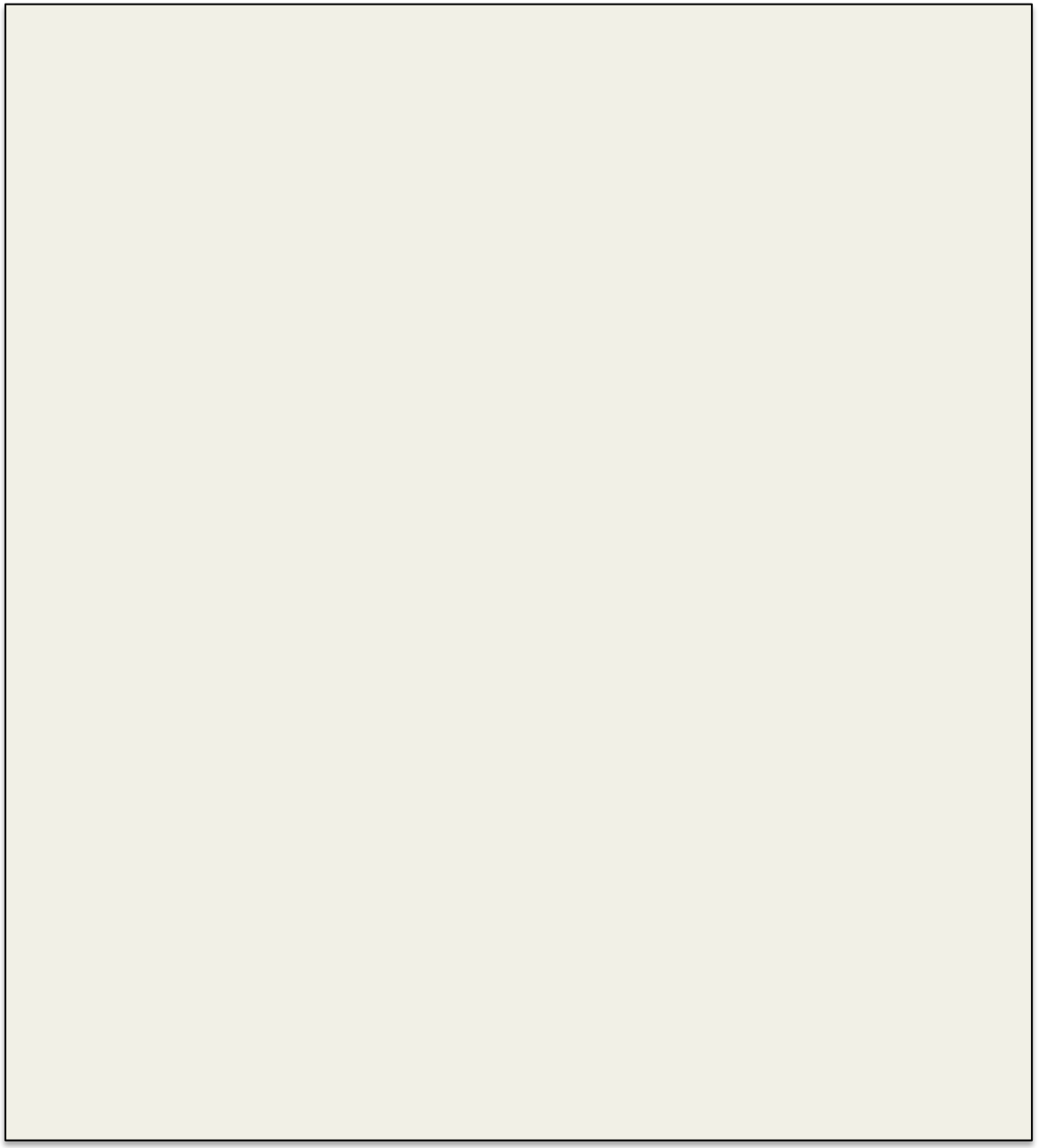
Advanced Topics

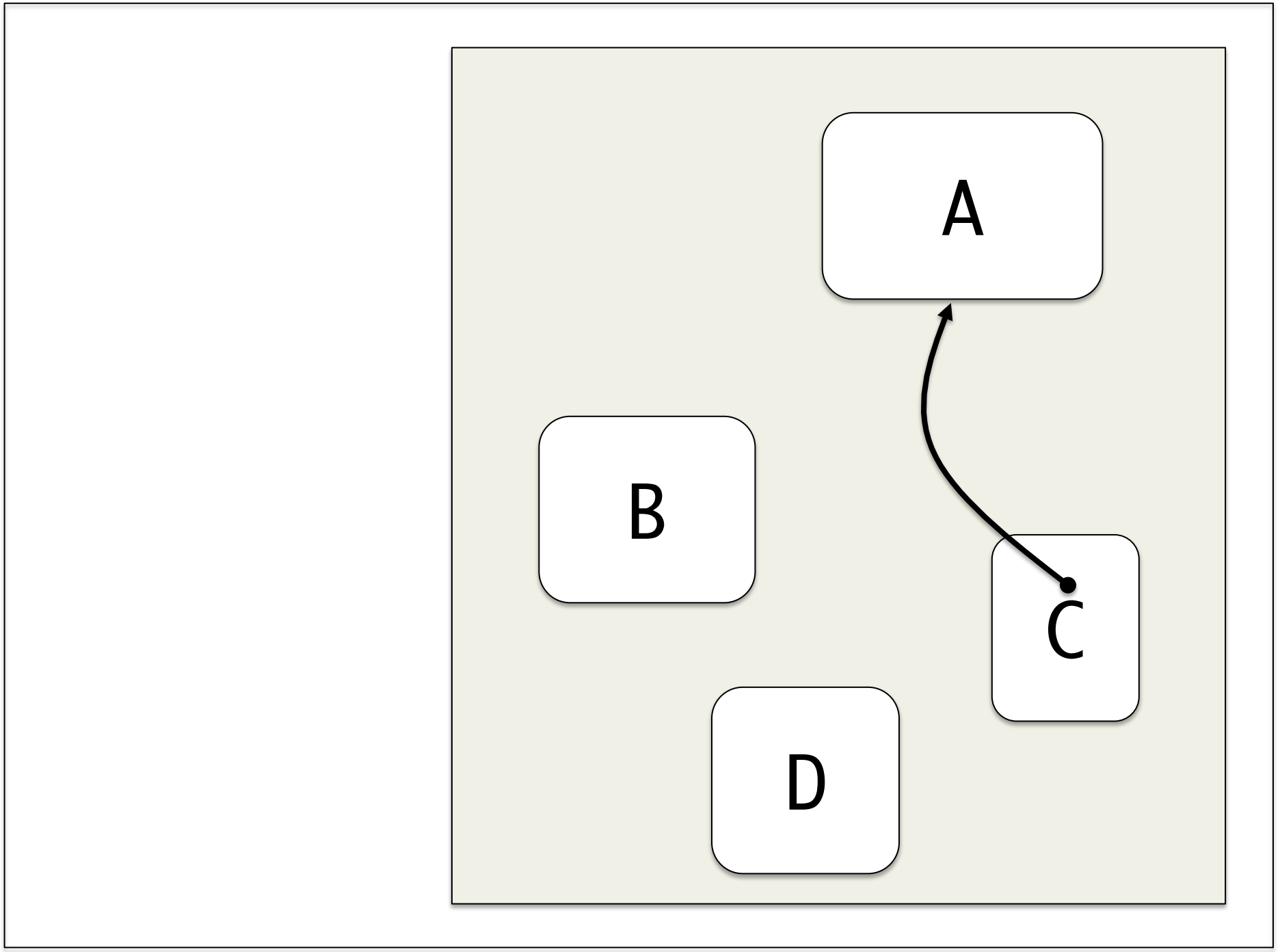


WEAK AND SOFT REFERENCES

GC Reachability

- Basic tracing model is simple
  - Roots define an entry point to the object graph
  - Live objects are reachable from the roots
- This model can sometimes be inconvenient
  - Not all references are equal
- Weak references allow reachability without liveness
  - Objects referred to only by weak references are garbage

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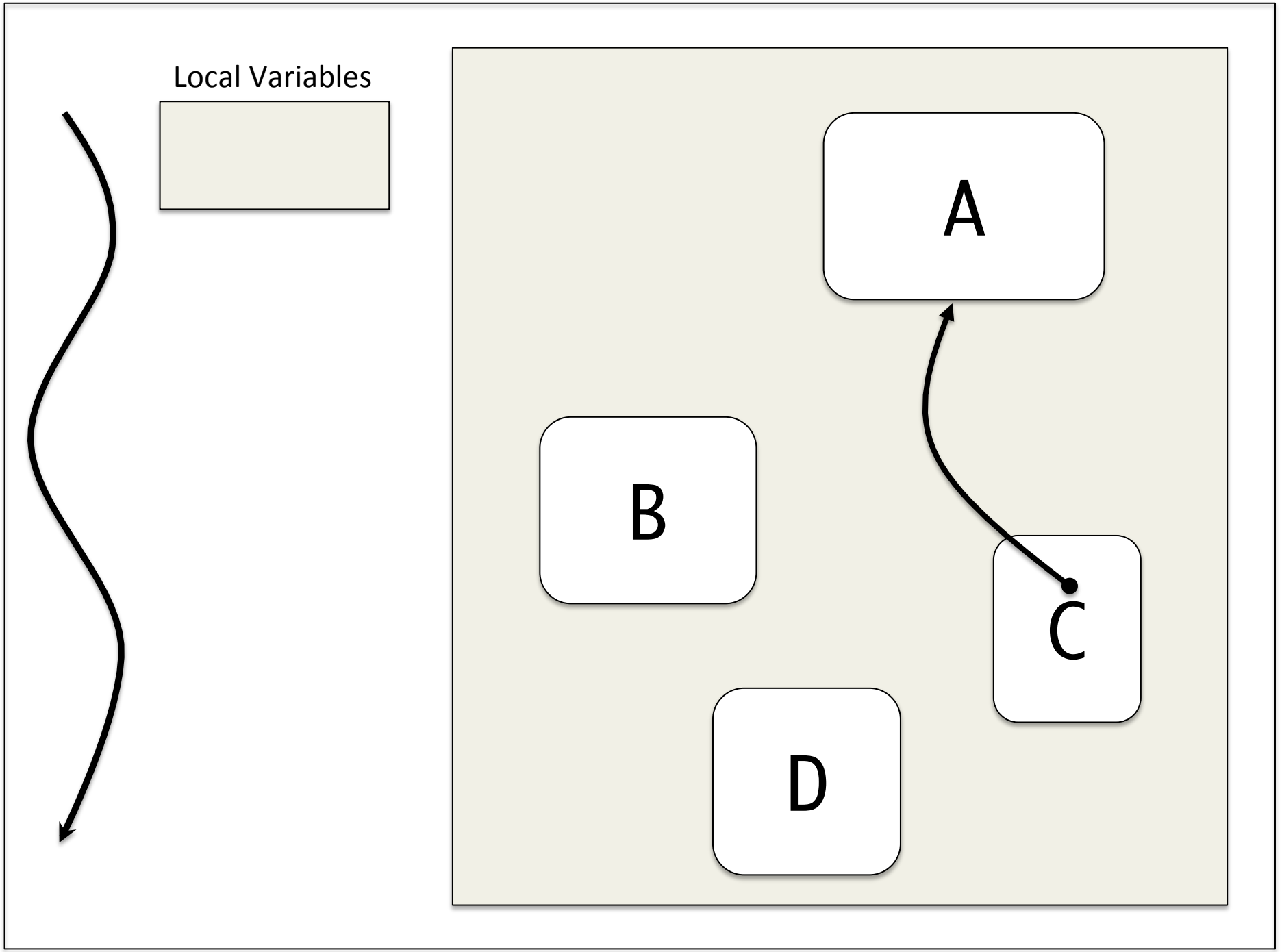
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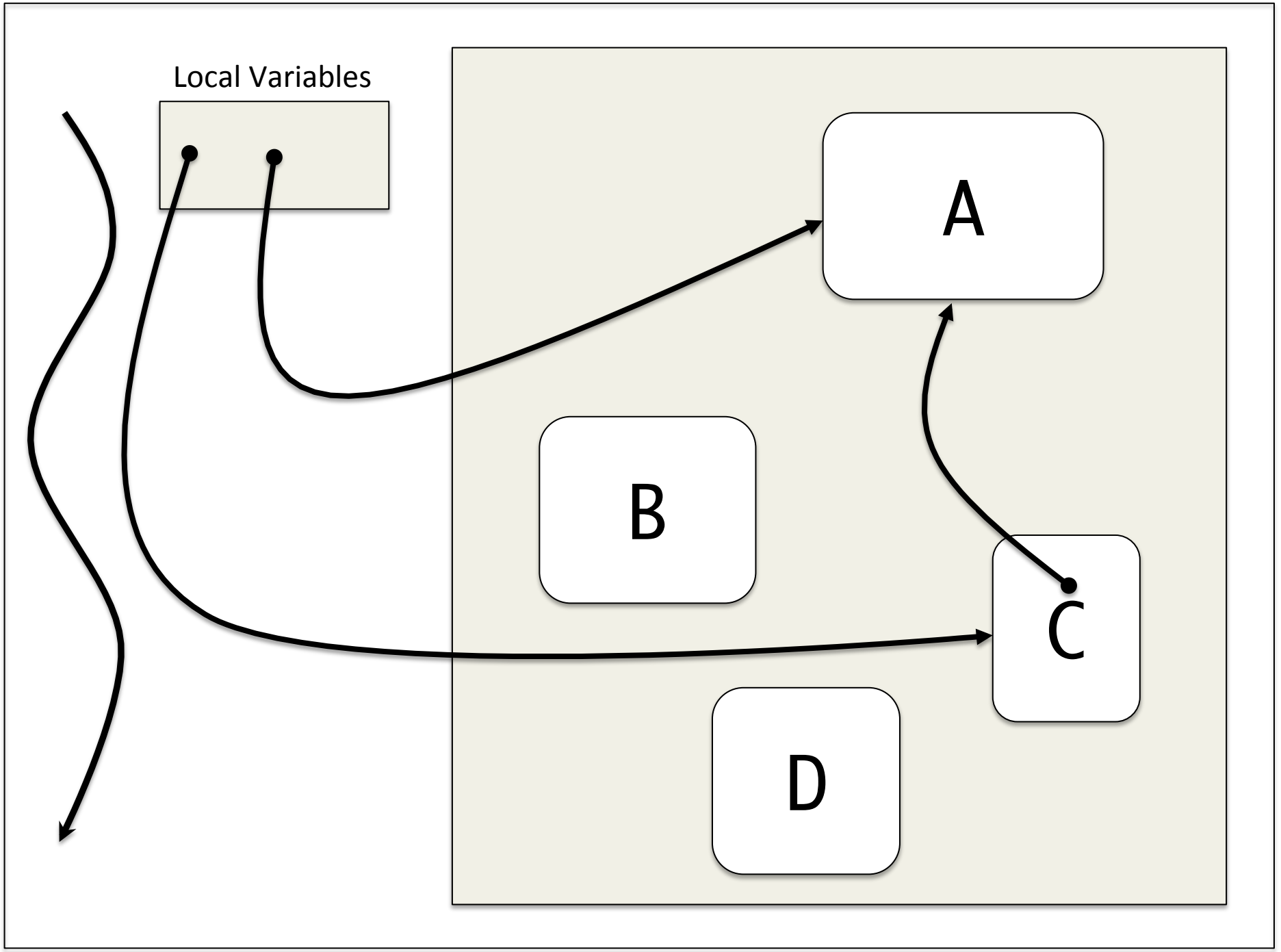
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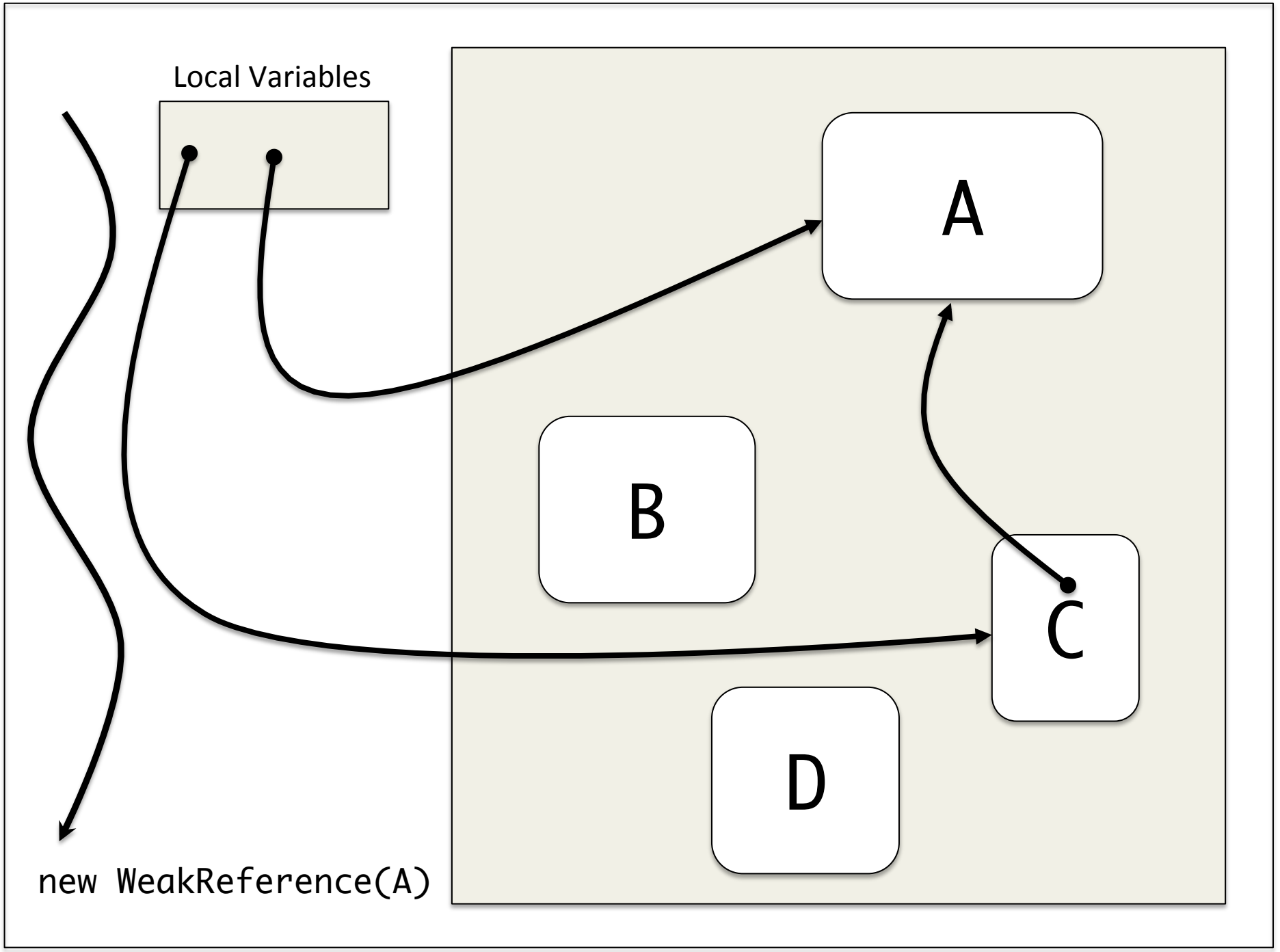
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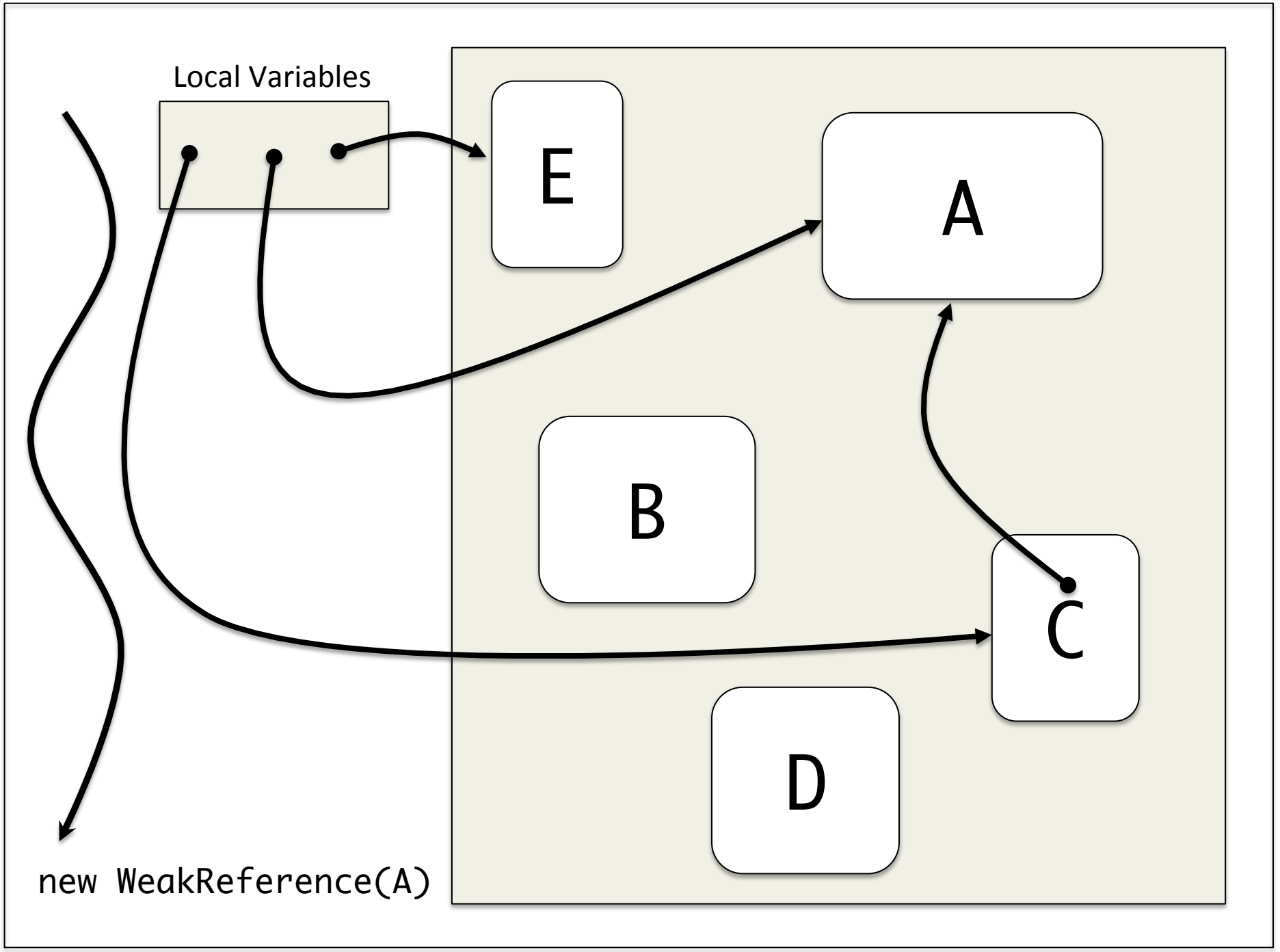
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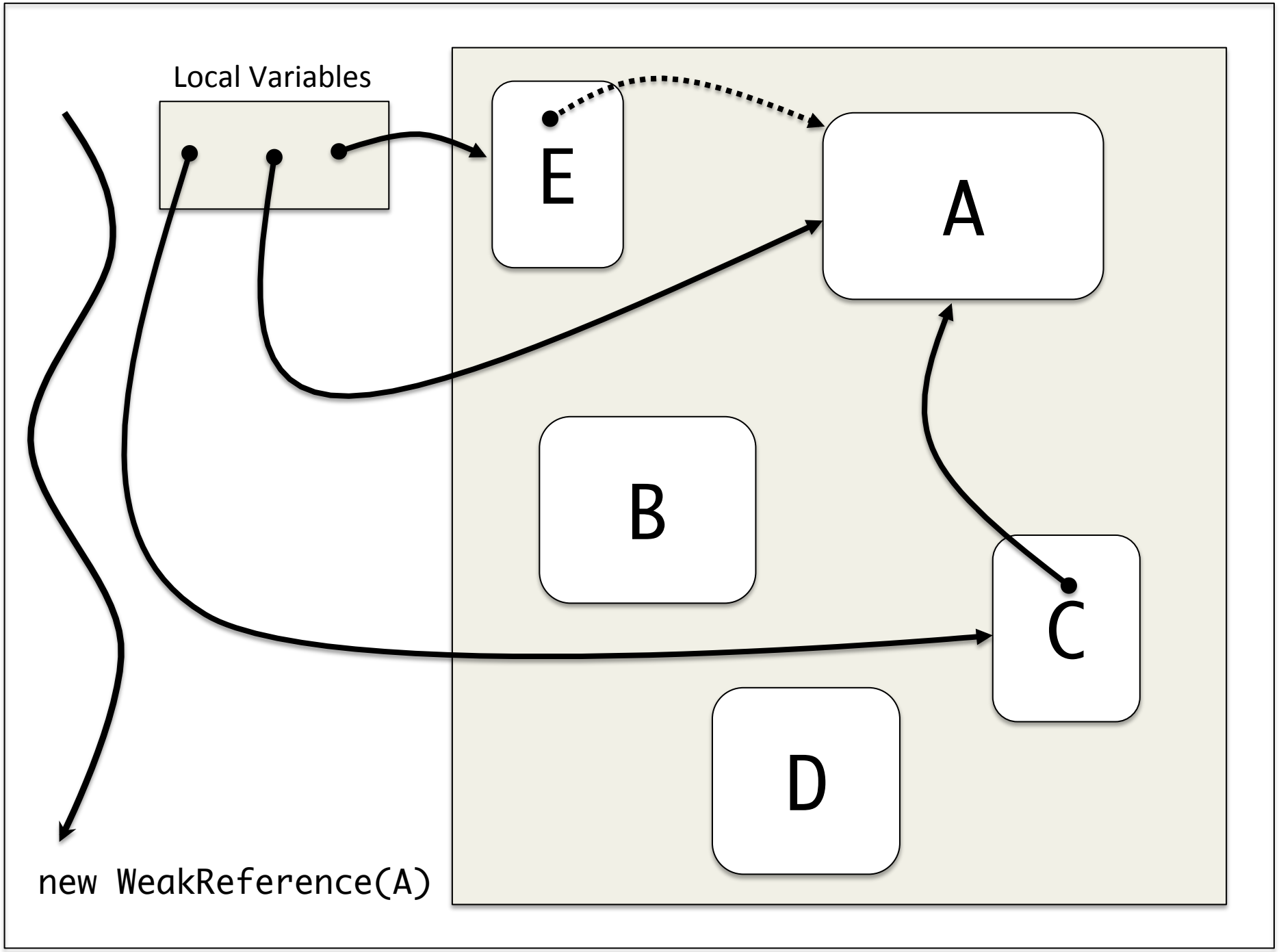
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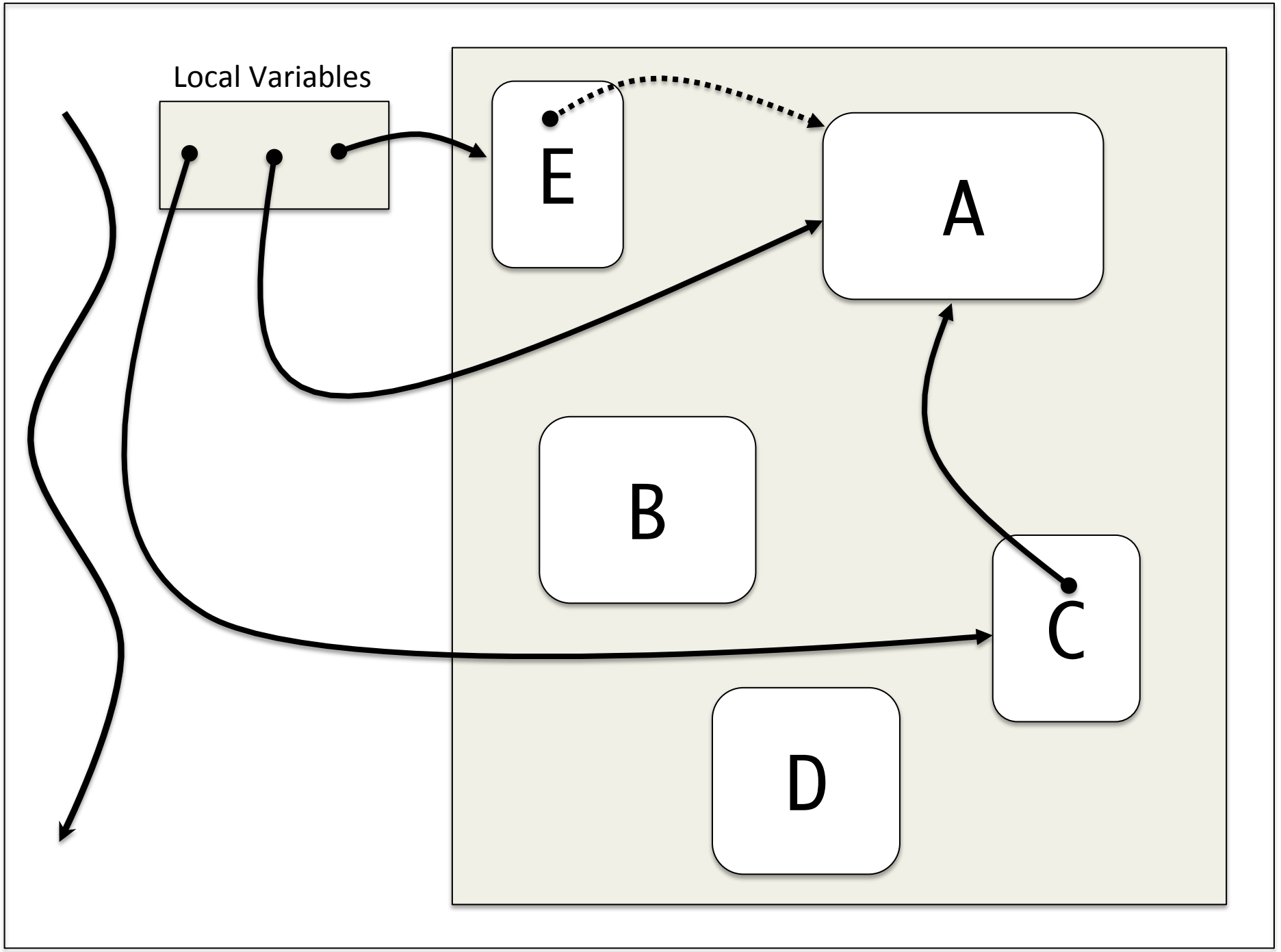
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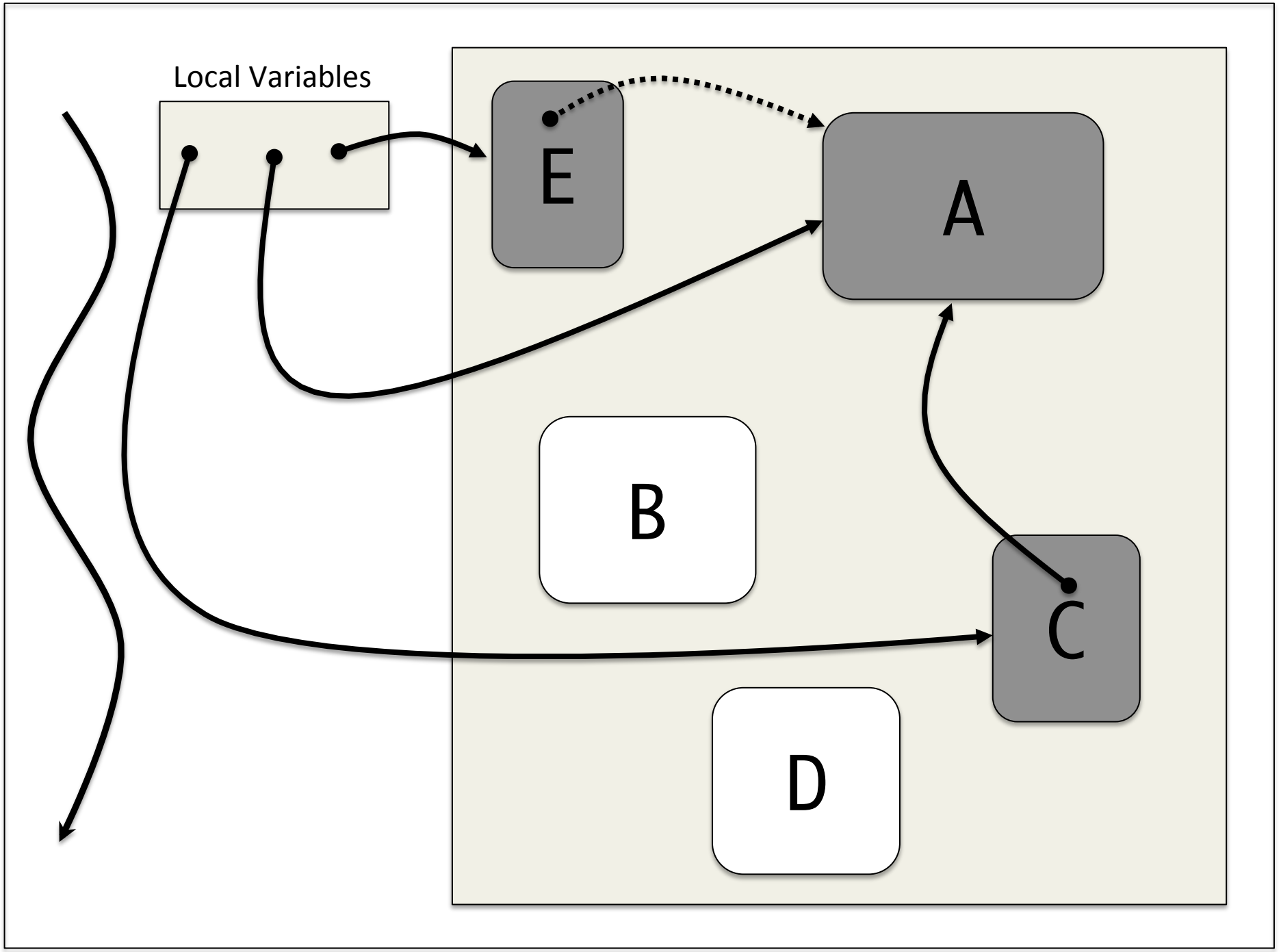
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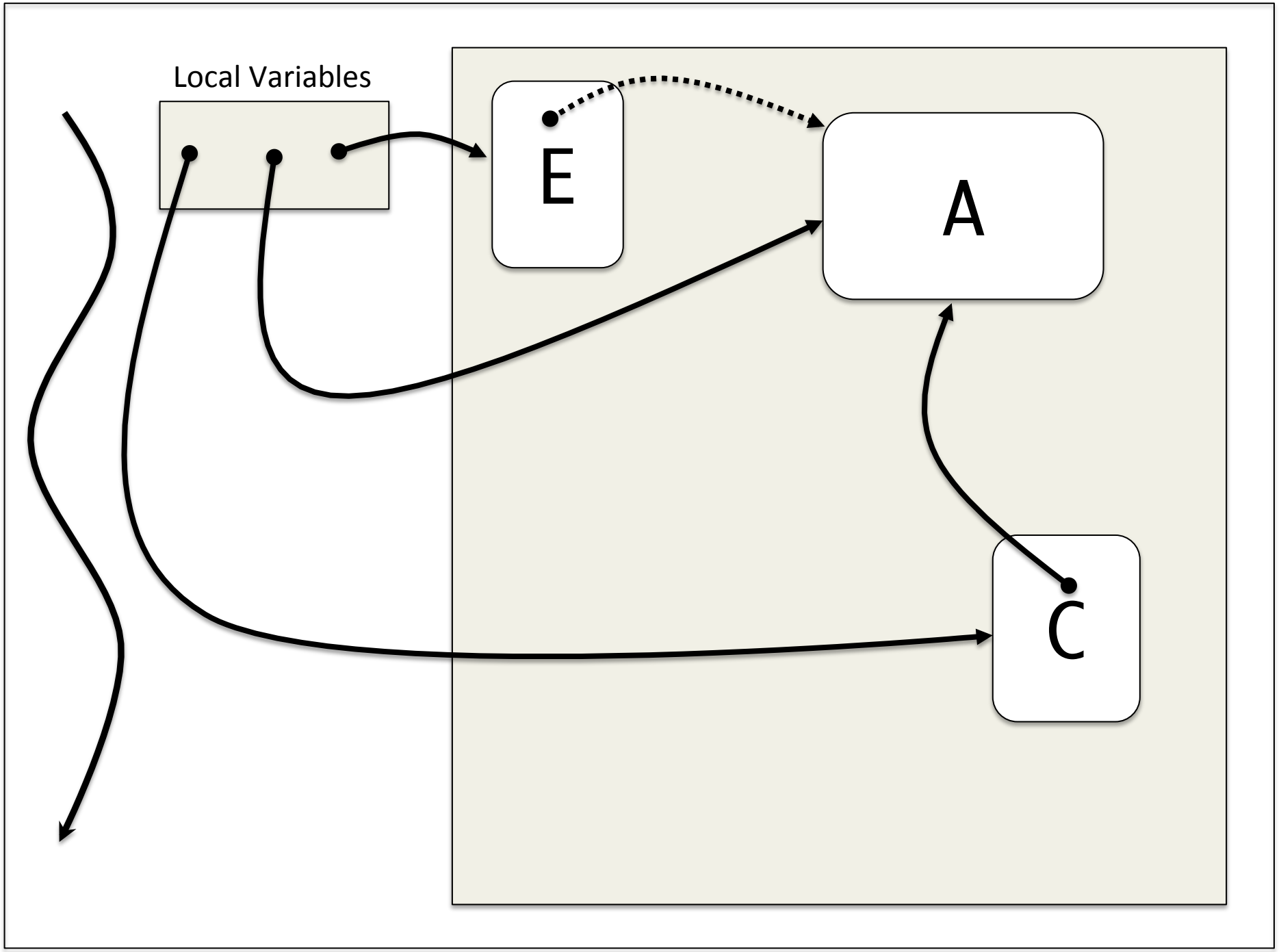
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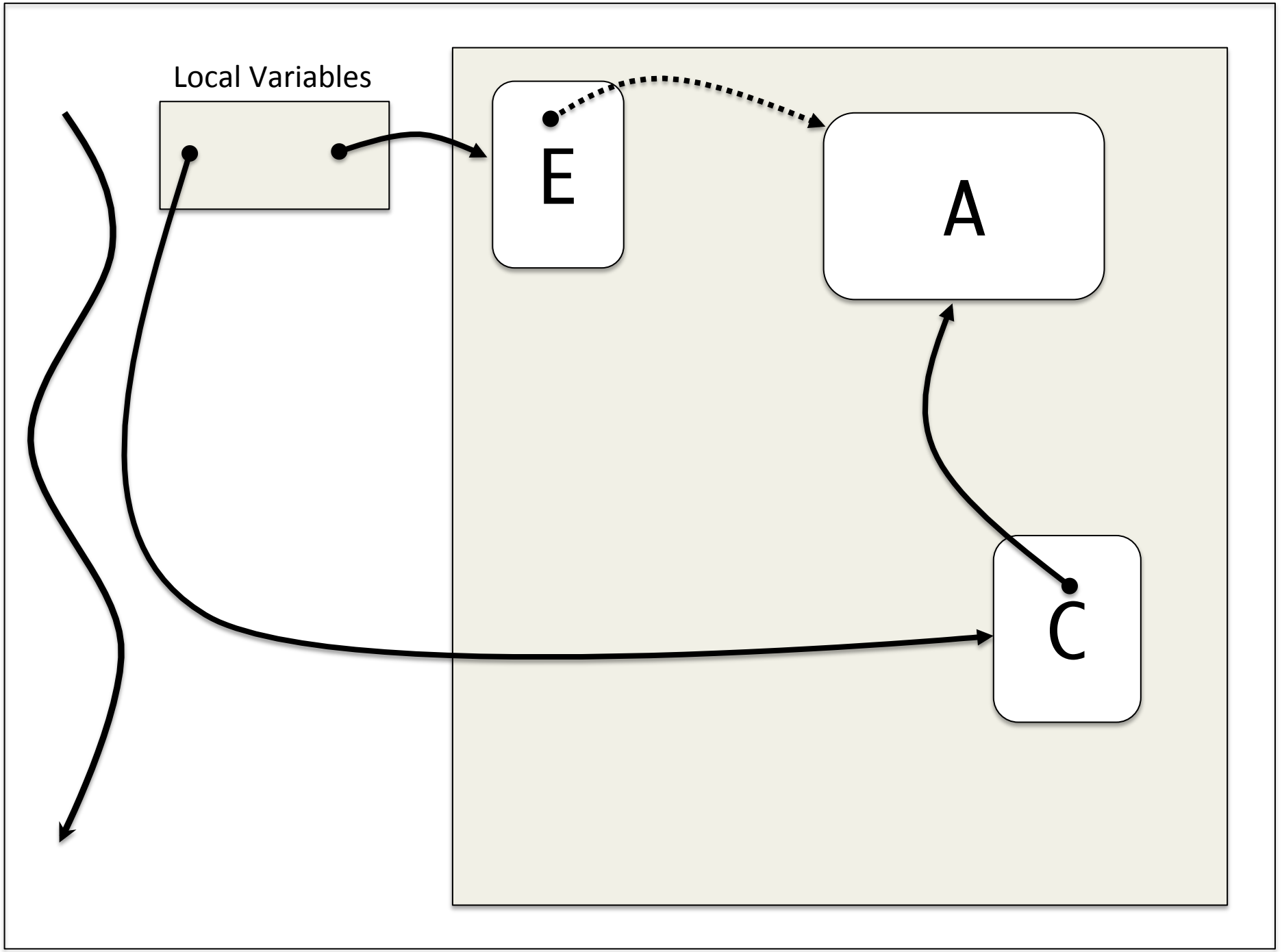
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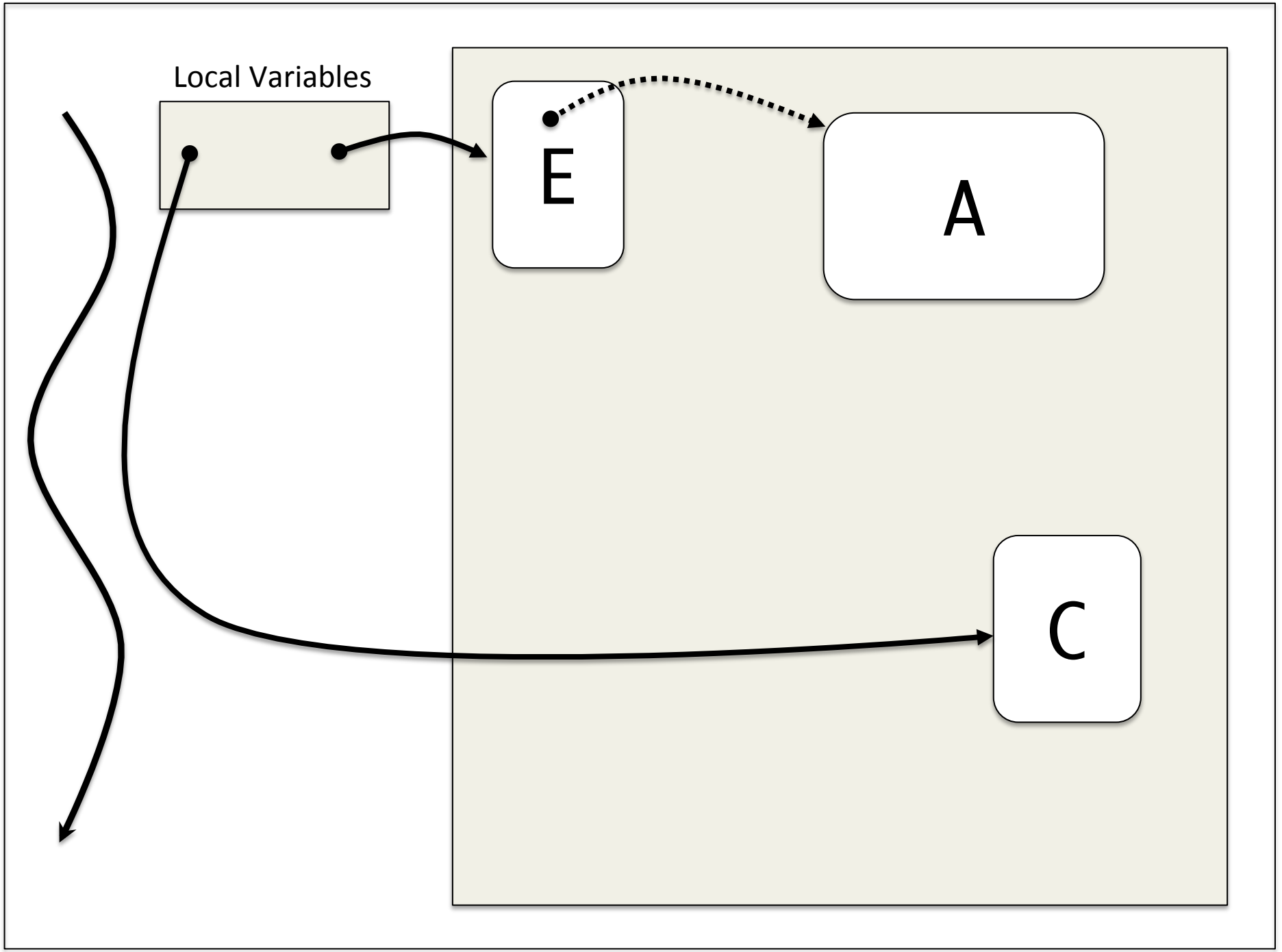
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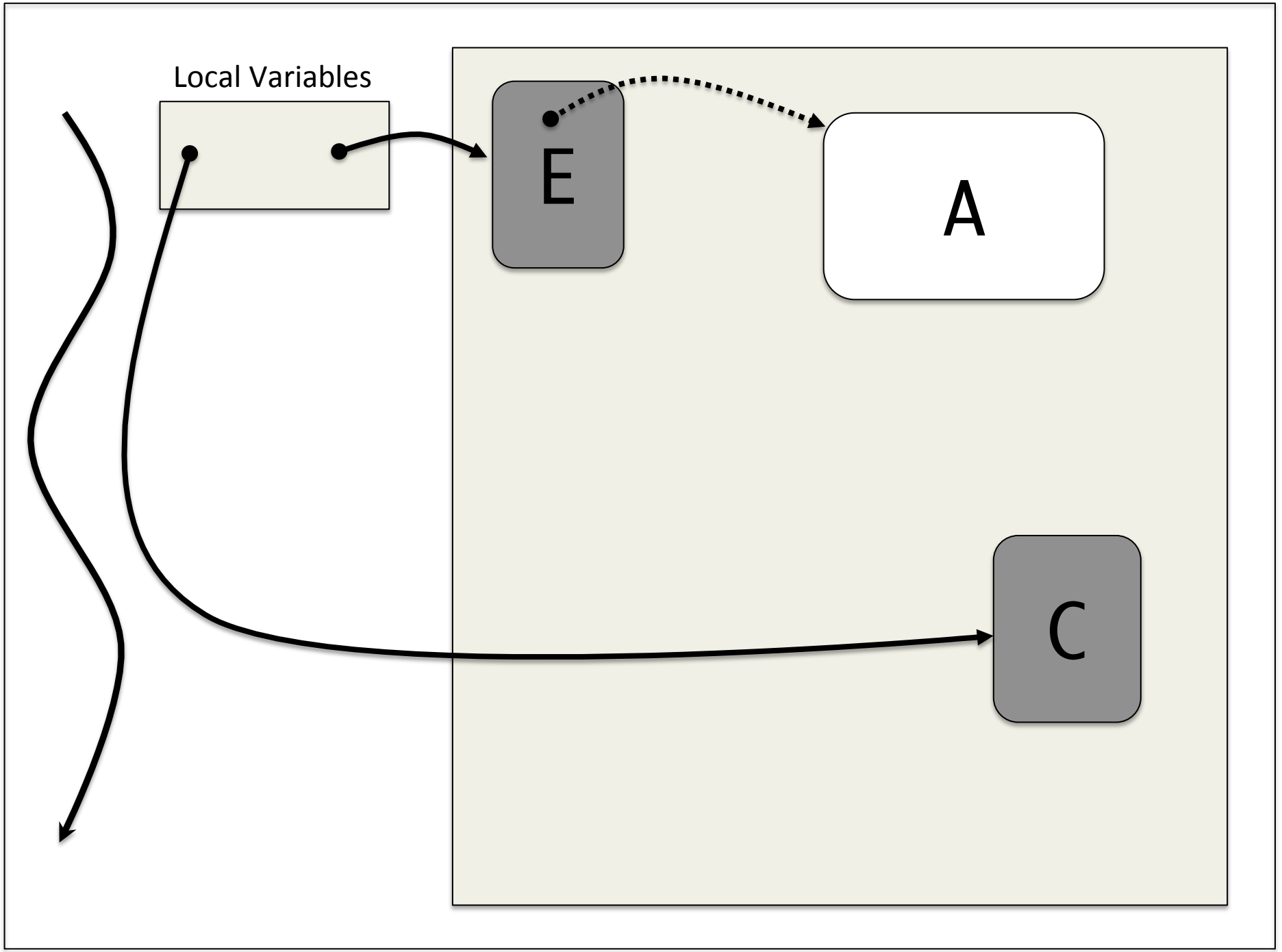
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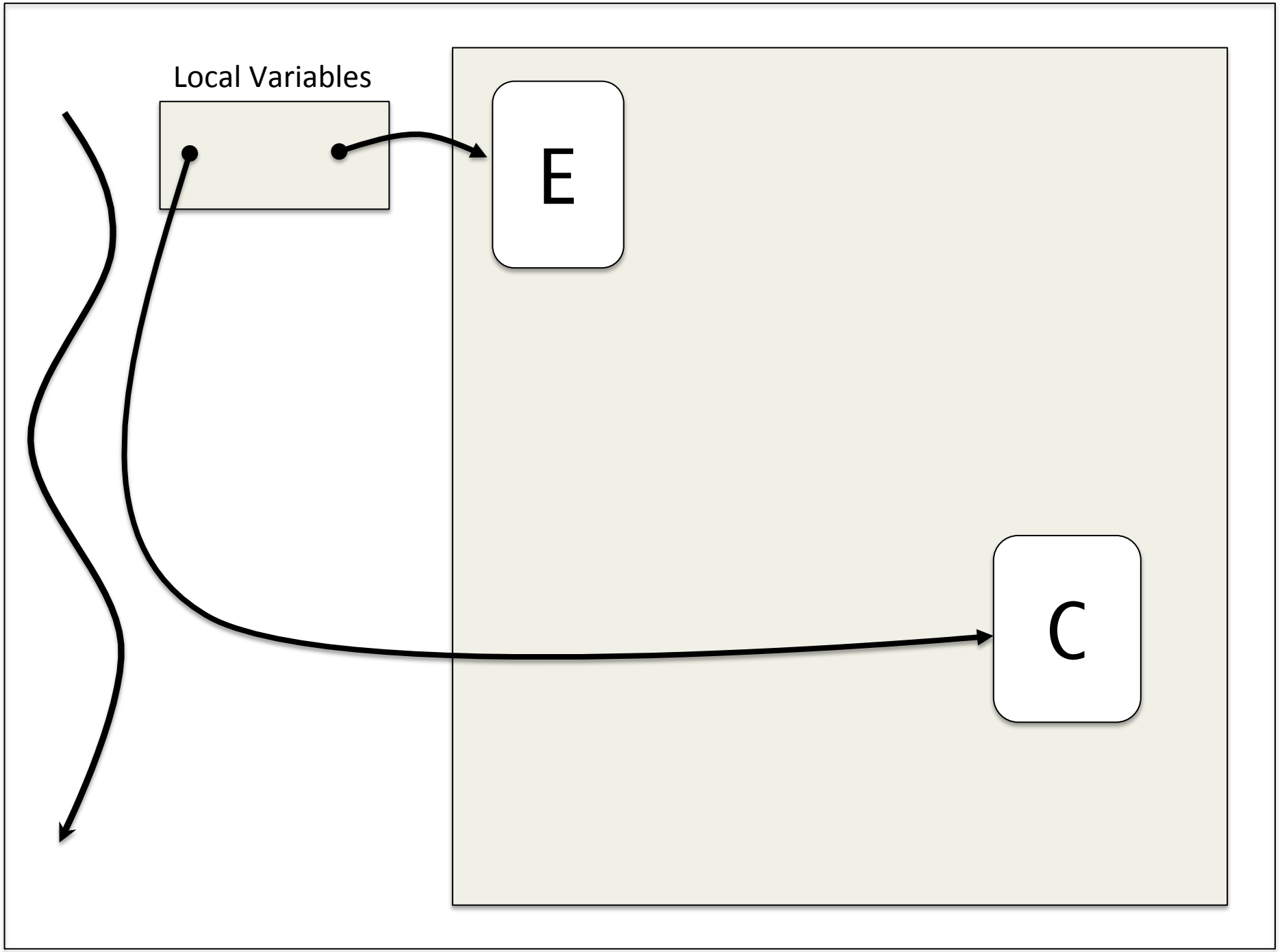
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Weak Reference Uses

- Associative caches
  - Object is the key, value holds extra information
  - Key shouldn't keep an object alive
- Reference cycles
  - Long-standing issue with reference counting
  - Make one reference is a structure weak
- Observer pattern
  - Easily disassociate from event managers

Implementing Weak References

- WeakReference class has special semantics
  - Tracing algorithms treat it differently
  - Value may be changed by the garbage collector
- WeakReference is a primordial class
  - VM doesn't allow redefinition
  - Referent field is volatile
- GC must keep track of weak references
  - Need to nullify them if the object is collected

Reference Queues

- Gives visibility into object reachability
  - Weak reference is registered with a queue
- GC adds reference to the queue when nullifying
  - WeakReference object is placed on the queue
  - Referent is freed
- Developer can check for objects on queue
  - Knows which objects have been freed
  - Can take action on other related objects

Soft References

- Similar semantics to weak references
  - Soft reference does not keep object alive
  - Represented as a separate object in the Java heap
- Soft references are not cleared immediately
  - Softly-reachable object may survive multiple GCs
  - Free depends on memory pressure
- Guaranteed to be cleared before OutOfMemory

Using Soft References

- Large data structures that can be re-created
  - Result of complex computation
  - File, network or database resources
- Store structures in memory for fast access
  - Refer to cached structure using soft refence
  - Freed when the GC needs to reclaim the memory
- Program performance tied to GC algorithm

Freeing Soft References

- Free schedule is implementation specific
  - Can happen at any time from developer perspective
  - Spec guarantees that it is before memory runs out
- May want to release objects incrementally
  - GC tends to run slowly when memory is tight
  - Massive free operation leads to large pause
- VMs implement caching algorithms

Soft References in Hotspot

- SoftReference object has a timestamp
  - Set to the time of the last GC
  - Shows roughly when the reference was last accessed
- GC knows how much live data is in the heap
  - Figures out based on the mark phase
- Pre-set ratio of survival time to garbage ratio
  - Each GC has a dynamic limit on time since last use
  - Least recently used objects are freed first

Phantom References

- Third type of reference object in Java
  - Not commonly used
- Serves only as a notification of collection
  - Associate a PhantomReference with a ReferenceQueue
  - Test for the reference to be added to the queue
- Allows for complex clean-up behavior
  - Unpredictable

Reachability Hierarchy

- Strongly reachable
  - Can be reached by following normal references
- Softly reachable
  - Reachable only through soft references
- Weakly reachable
  - Reachable only through weak references
- Phantom reachable
  - Reachable only through phantom reference
- Unreachable
  - No references to the object

FINALIZATION

Destructors

- Destructors are a common concept
  - Code that runs when an object is freed
  - Useful for cleaning up resources
- Implementation in C++ is intuitive
  - Two types of storage – stack and heap
  - Stack objects freed when they leave scope
  - Heap objects have explicit free call
- Destructors run at well-understood times

Finalizers

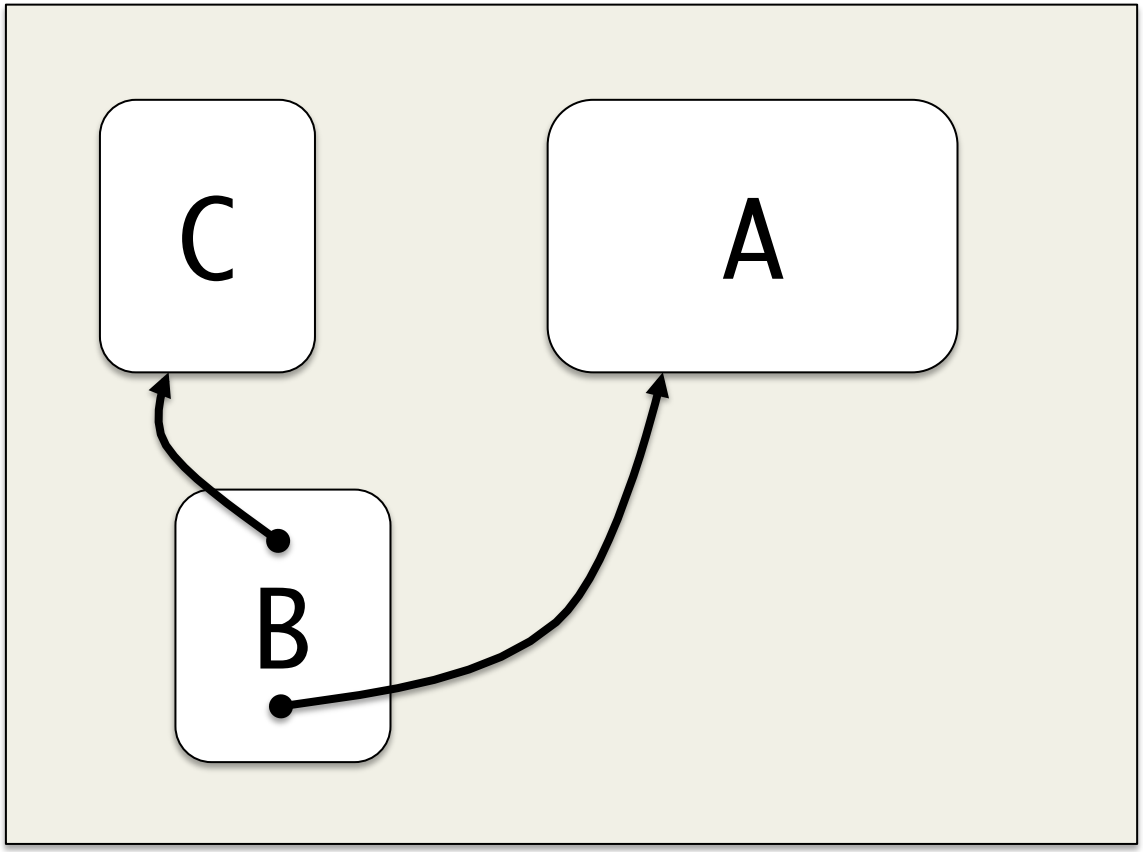
- Similar concept in managed languages
  - Any Java class can override Object.finalize() method
  - Called when an object is reclaimed by the GC
- Two key differences
  - Timing of finalizer is unpredictable
  - Finalization done in a separate thread or threads
- Finalize methods are harder to get right

Finalization Semantics

- Finalize method can contain any Java code
  - Recommended use is to clean up resources
- Finalization is handled by a daemon thread
  - Thread guaranteed not to currently hold any locks
- Exceptions thrown by a finalizer are ignored

Implementing Finalization

- Maintain a finalization queue
  - Check for a finalizer when freeing an object
  - May also flag finalizable objects at allocation time
- Add to the queue only before freeing the memory
  - Finalizers run before the memory is re-used
  - Some algorithms don't reuse all parts of the heap
- Run finalizers incrementally or concurrently
  - Finalizers can interact with other threads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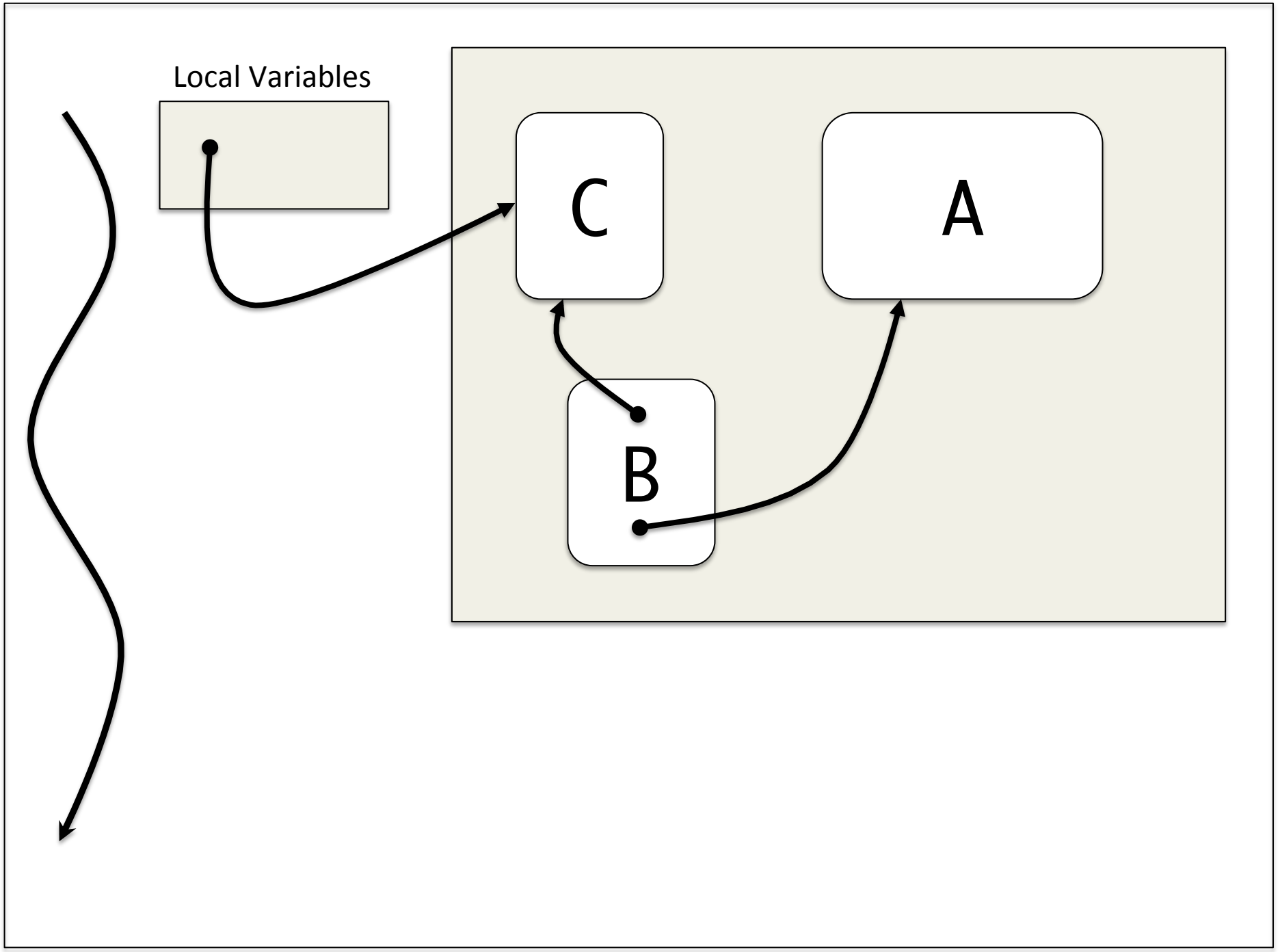
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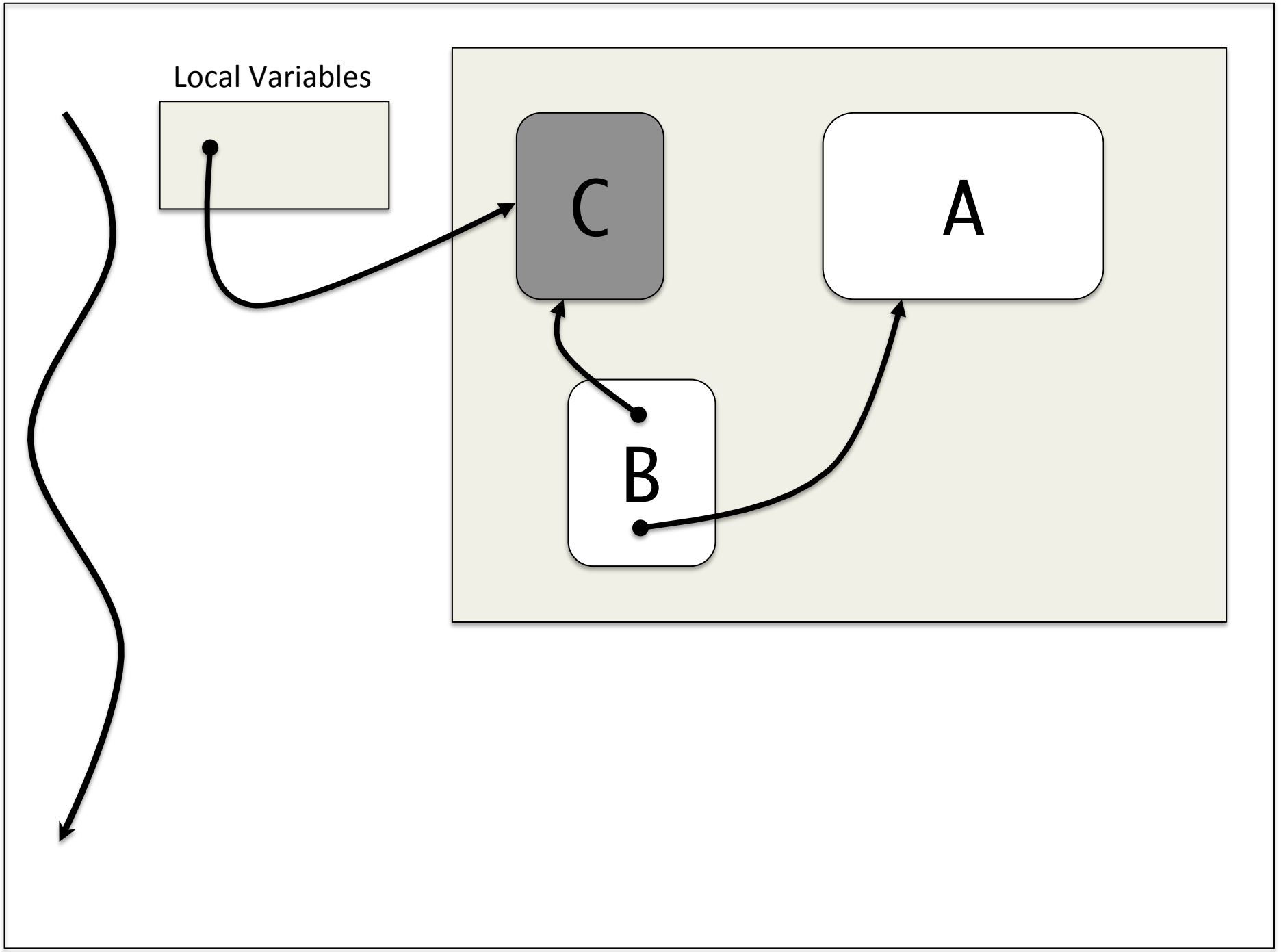
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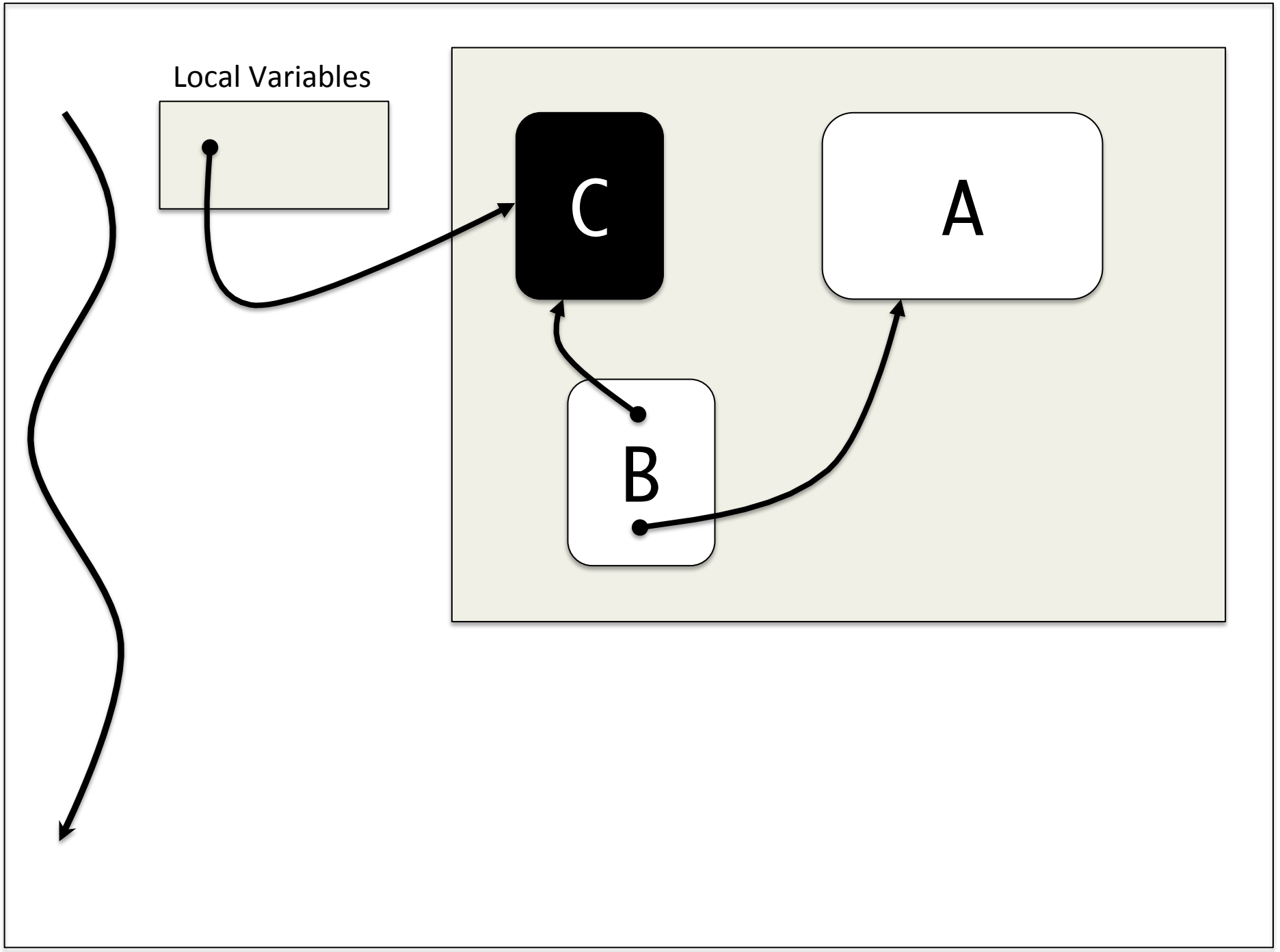
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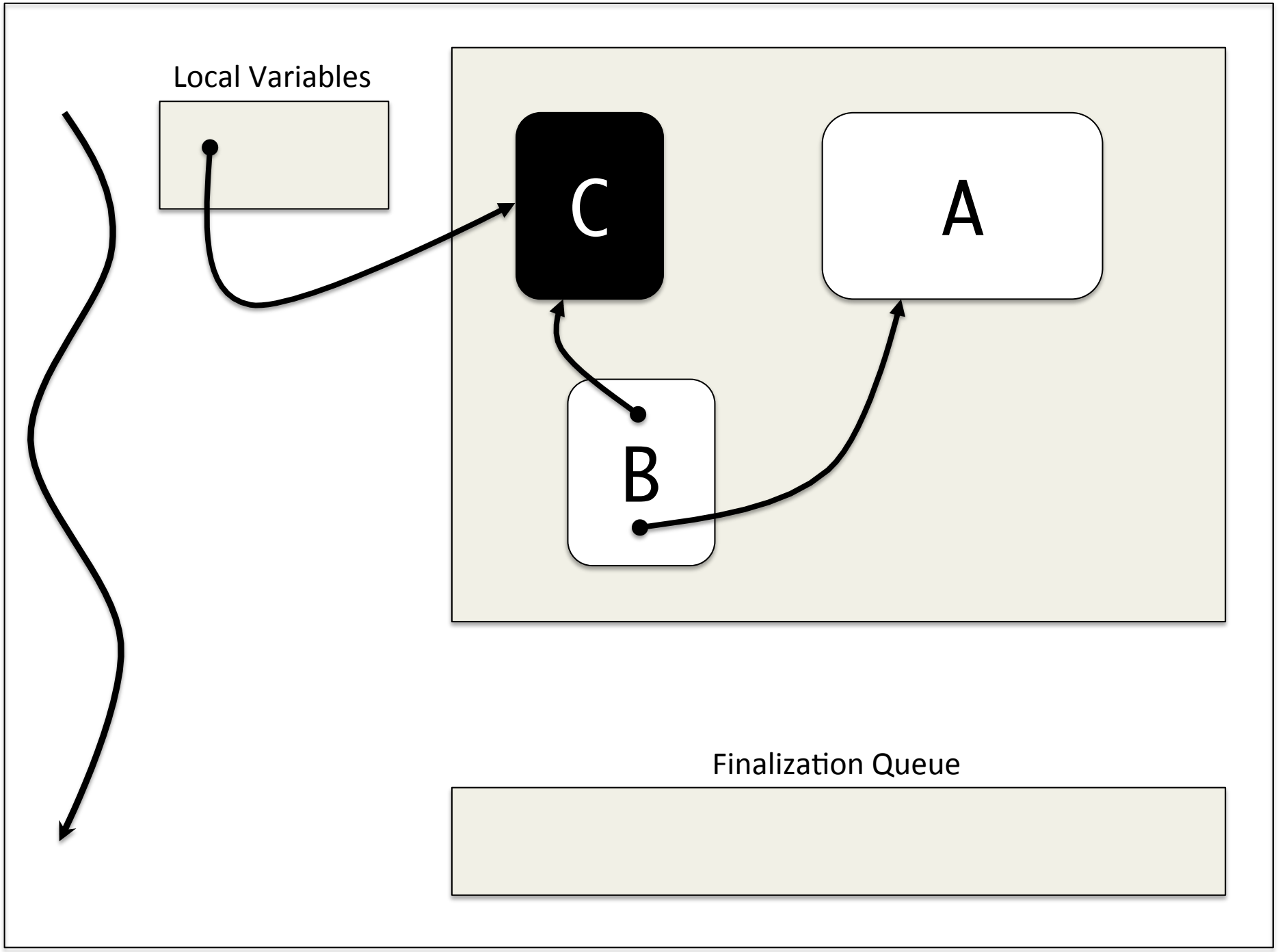
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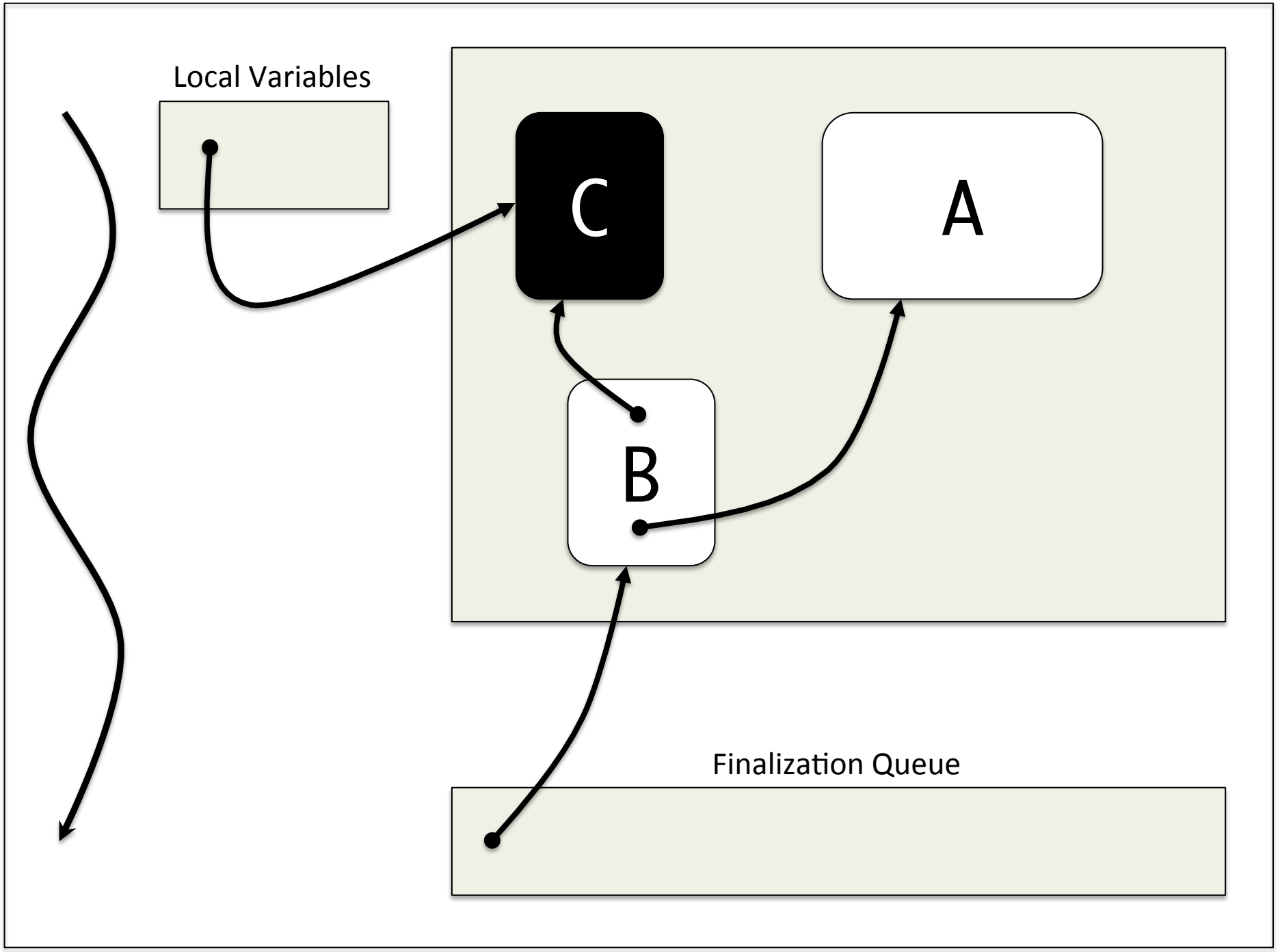
Finalization Queue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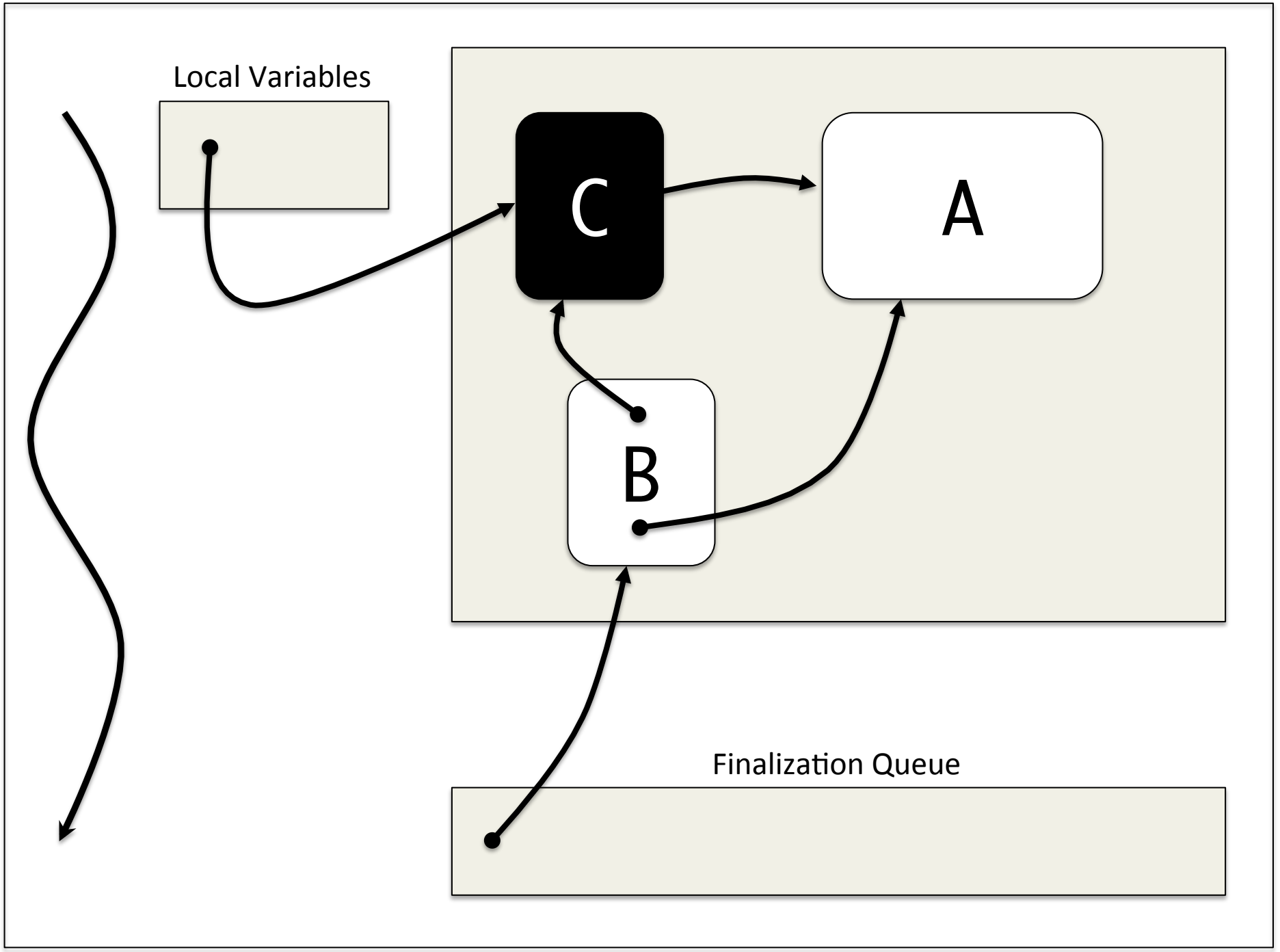
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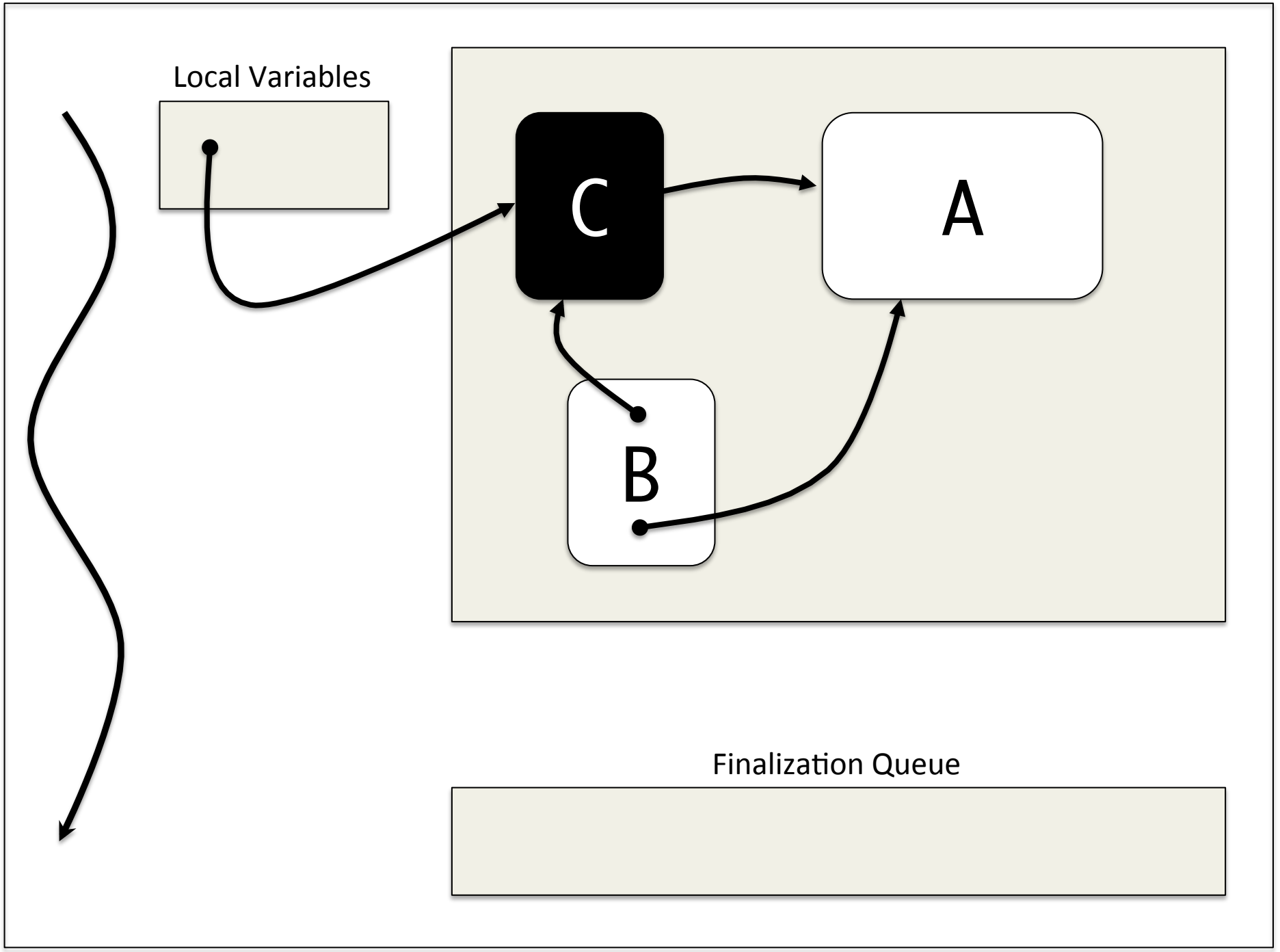
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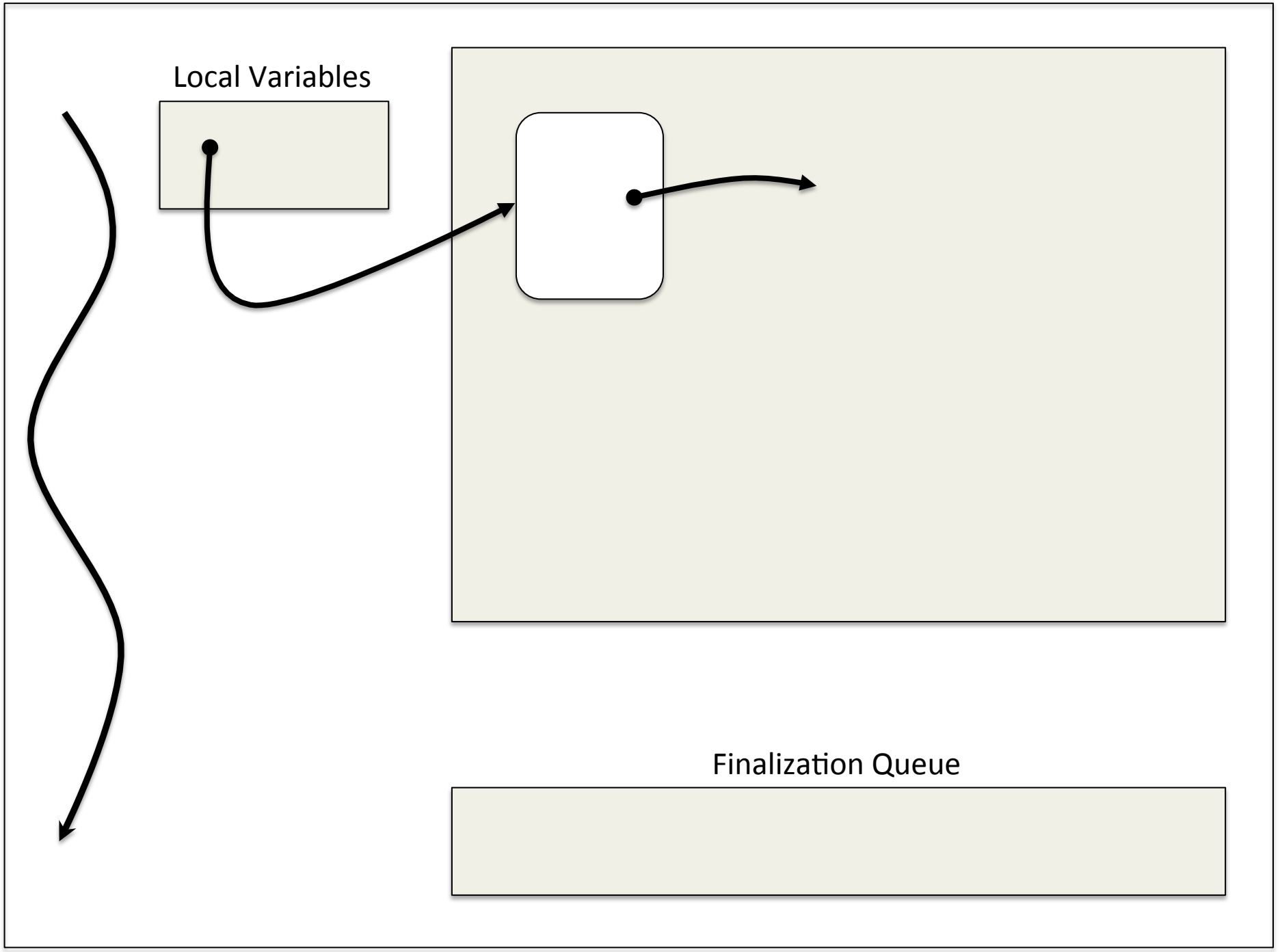
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Finalization Queue

Object Resurrection

- A finalizer can make a garbage object reachable
  - May the the this pointer
  - May be another object entirely
- Resurrection greatly complicates GC
  - Can't delete any object that may be referred to
  - Need to wait until all finalizers run before deleting
- Can use a two-phase approach

Phased Finalization

- Trace the heap to find objects to be freed
  - Applies to all tracing algorithms
- Run all finalizers in the finalization queue
  - Remember that any object can only be finalized once
  - This phase may resurrect objects
- Trace the heap again
  - Identify object that are definitely garbage

Concurrent Finalization

- Some algorithms allow concurrent finalization
  - Extension of the phased finalization algorithm
- Works if garbage can be retained for a GC cycle
  - Ensure that all finalizers run before the next GC
  - Tracing phase of next GC finds unreachable objects
- Track phantom objects separately
  - Those found unreachable and not resurrected

Double Finalization

- A given object's finalizer is called at most once
- Resurrected objects may have different semantics
  - An object may be resurrected after finalization
  - Objects may resurrect themselves
- The object will not be finalized again

Multi-Threaded Finalization

- Objects are finalized by a finalizer thread
  - May be multiple parallel threads
  - Could be a specialized daemon
- The VM can borrow an application thread
  - Must ensure that no locks are held
  - Incremental finalization on constrained systems
- Finalizers can cause deadlock

Why Use Finalizers

- Free up native memory
  - Natural extension to GC semantics
- Last-resort resource clean up
  - Log errors in explicit resource tracking
- Can be useful if you understand the semantics

AHEAD OF TIME COMPILATION

Ahead of Time Compilation

- AOT compilation is a familiar model
  - Write your code
  - Run the compiler
  - Ship the resulting executable
- Java AOT step is generally very minimal
  - Convert the Java code to bytecode
- AOT compilers can build executable from Java

AOT Advantages

- Shift compilation cost from the runtime
  - No interpretation and profiling phase
  - No JIT compilation
- Produce a static binary
  - Single image contains all required code
  - Can do whole-program analysis
- Well adapted to constrained environments
  - Low power prohibits JIT compilation
  - Uncooperative environments don't allow dynamic code

AOT Limitations

- Up-front compilation cost
  - Resulting executable is platform specific
- Can't use dynamic classloading
  - All classes must be declared ahead of time
  - Harder to adapt the application to the environment
- Limited profiling and debugging
  - JVMTI instruments bytecode
  - Requires interpreter or JIT compilation

Ahead of Time Compilers

- Various compiler implementations
  - GCJ
  - Excelsior
  - LLVM
- Compiler requires a class library implementation
  - Licensing issues with the standard JDK library
  - GNU Classpath offers partial compatibility

LLVM

- Open source compilation framework
- Various language-specific front-ends
  - Common intermediate representation
- Basis of various compilers in everyday use
  - Clang used as a replacement for GCC
- VMKit was a JVM leveraging LLVM
  - LLVM + MMTk + pthreads + glue

GC in LLVM

- Limited support for garbage collection
  - Doesn't provide an actual GC implementation
  - Provides hooks for runtime developers
- Binary interface in LLVM support intrinsics
  - Creating GC safepoints
  - Computing stack maps
  - Read and write barriers
- Intermediate representation supports other aspects
  - Type maps
  - Root locations

LLVM as a JIT

- LLVM was thought to be static only
  - Optimizations required large analysis
  - Doesn't take advantage of profiling data
  - Support for mixed mode operation limited
  - Compilation is much slower than required
- Apple released LLVM-based JIT in Webkit
  - Dynamically compiling Javascript in Safari
  - Significant engineering work

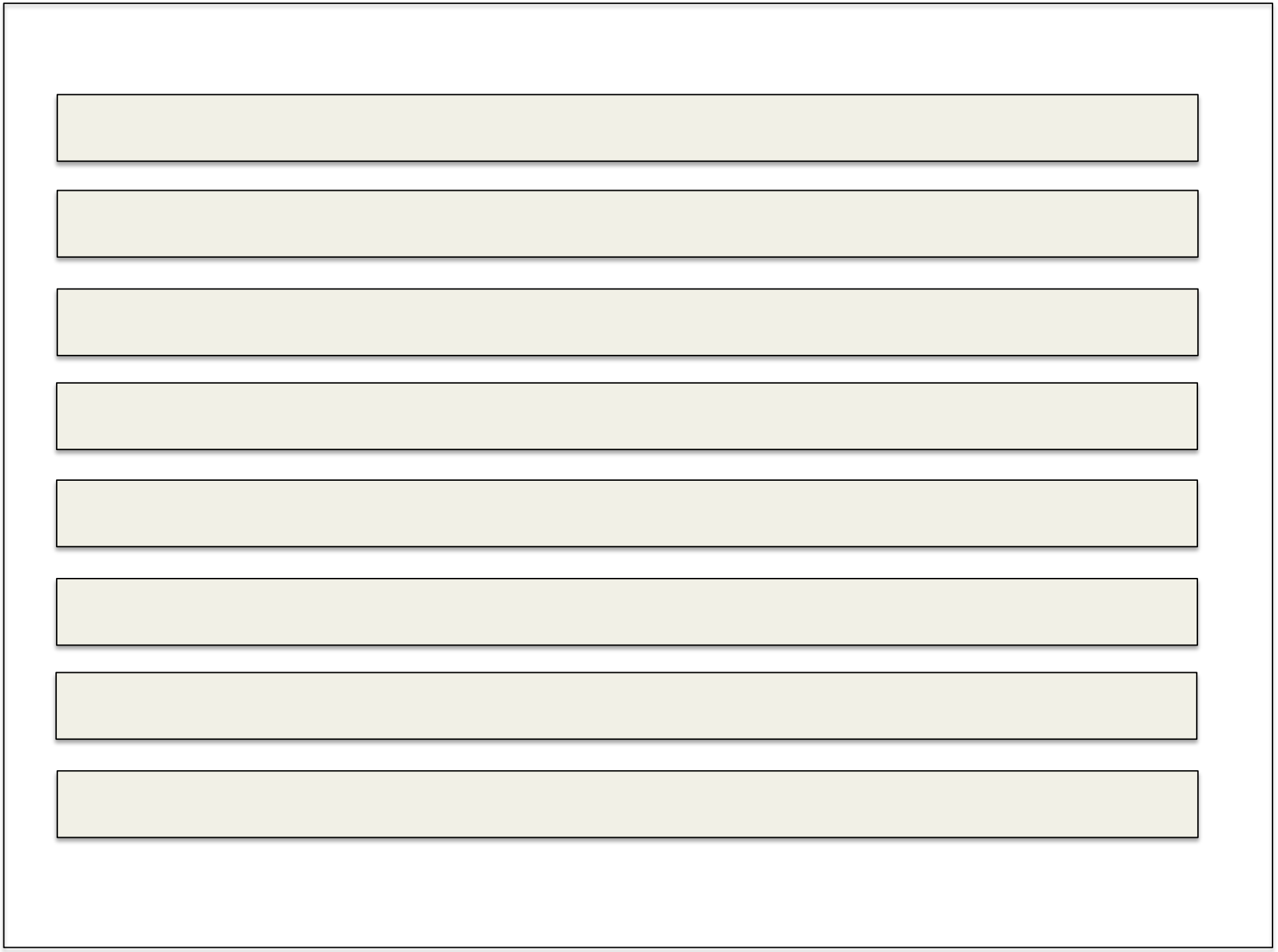
GARBAGE FIRST ALGORITHM

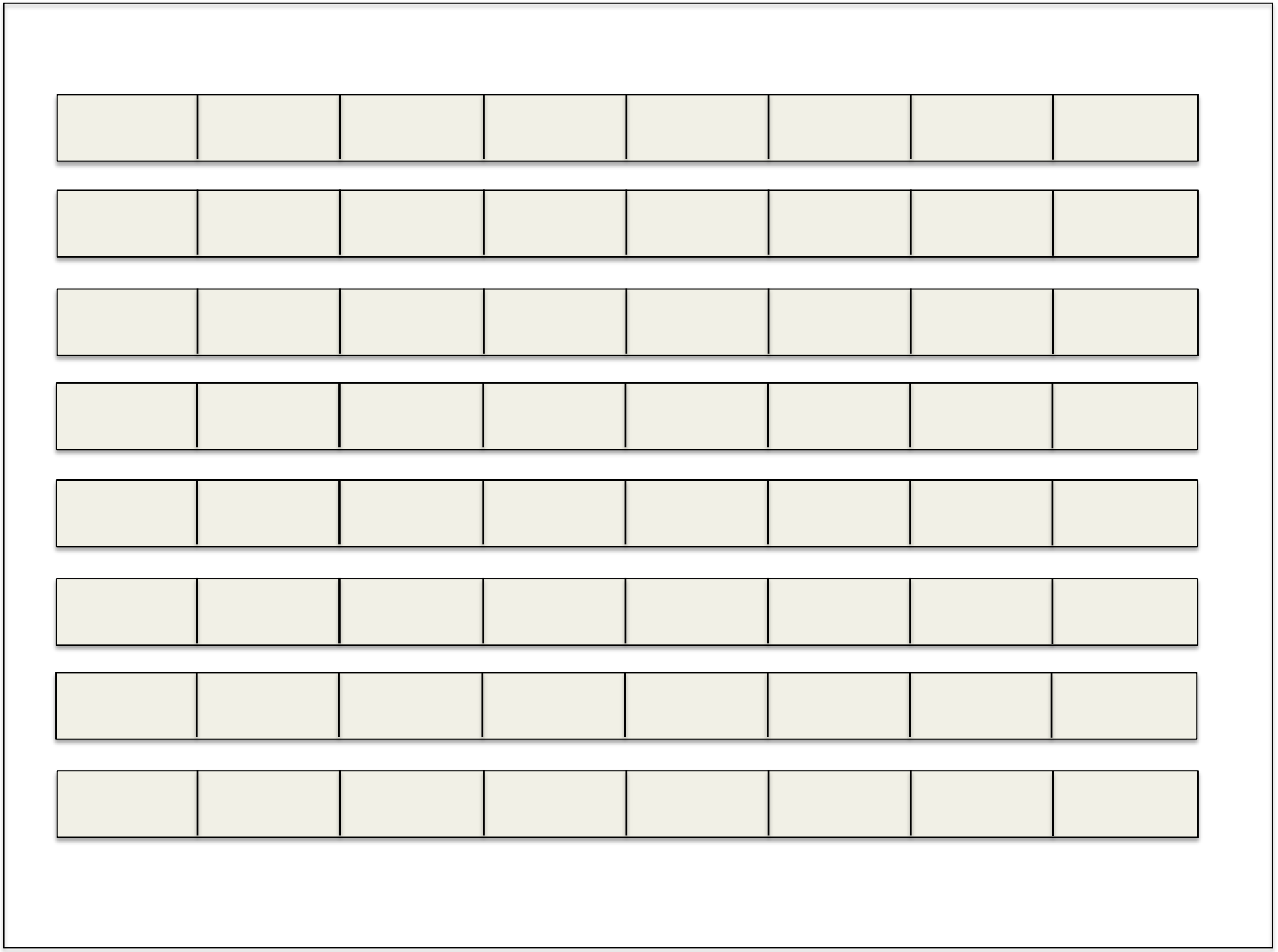
Garbage First Algorithm

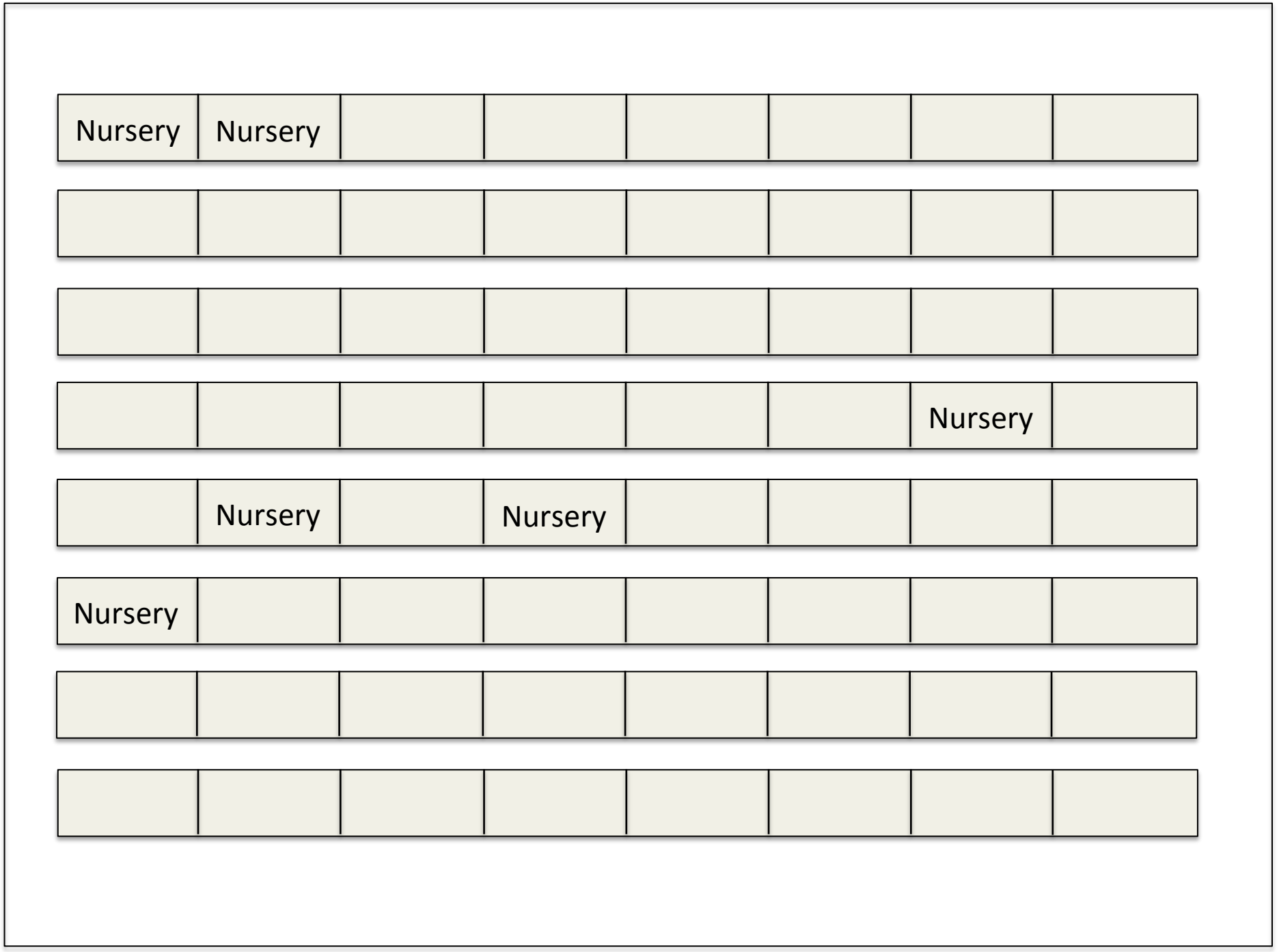
- Latest iteration of the Hotspot collector
  - Not enabled by default
  - Targets pause times over throughput
  - Many server applications want the inverse
- GC is parallel and concurrent
  - Copies objects to compact the heap
  - Pauses are predictable and tunable
  - Offers soft real-time without guarantees

G1 Regions

- Heap is split into equally-sized regions
  - Region sizes range from 1-32 Mb
  - Aim to have no more than 2048 regions
  - More tuning to enable more than 64 Gb heap
- Young generation made up of two block types
  - Nursery (or Eden)
  - Survivor set
- Very large objects given a region to themselves
  - Multiple regions can coalesce if necessary



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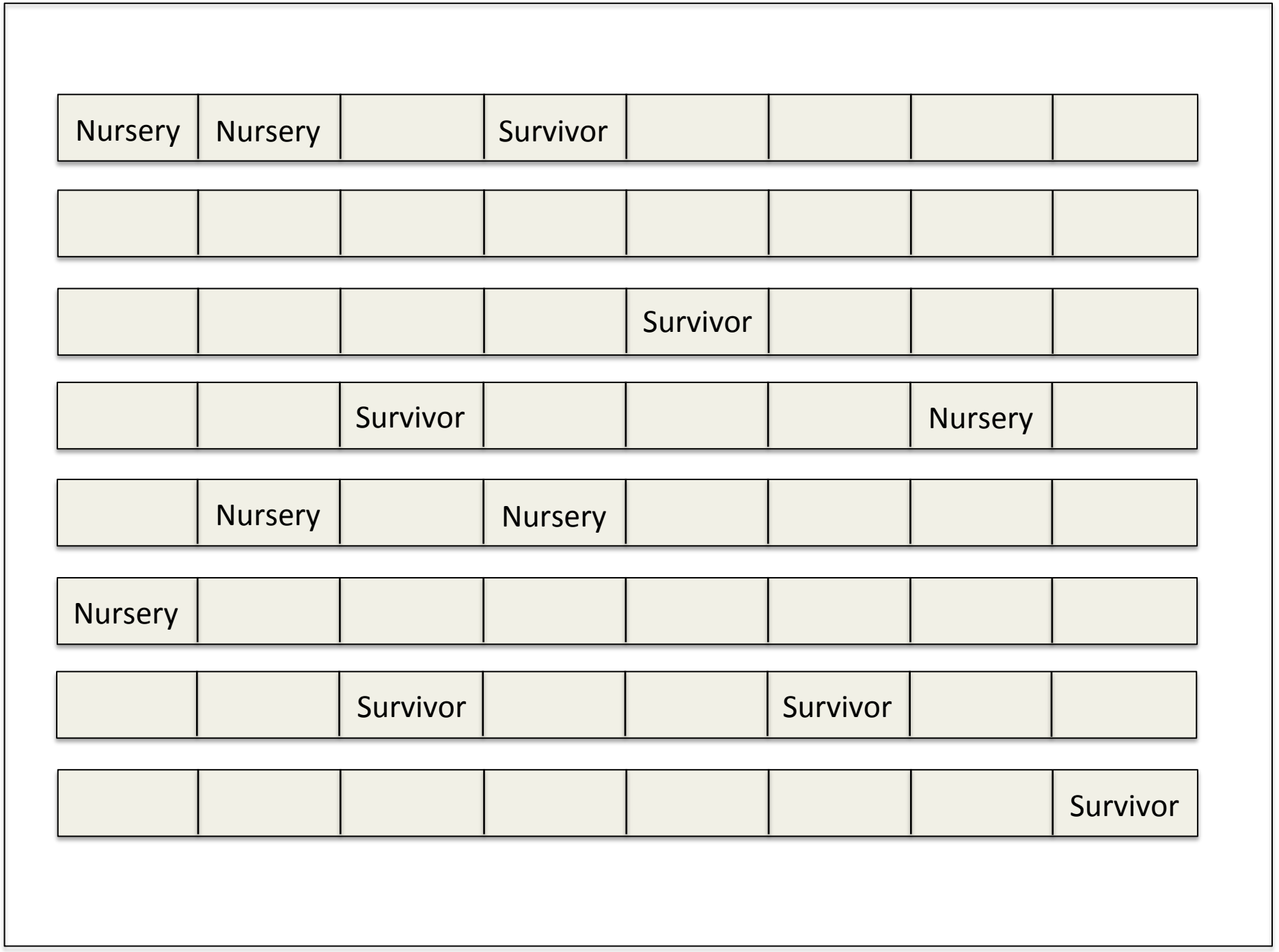
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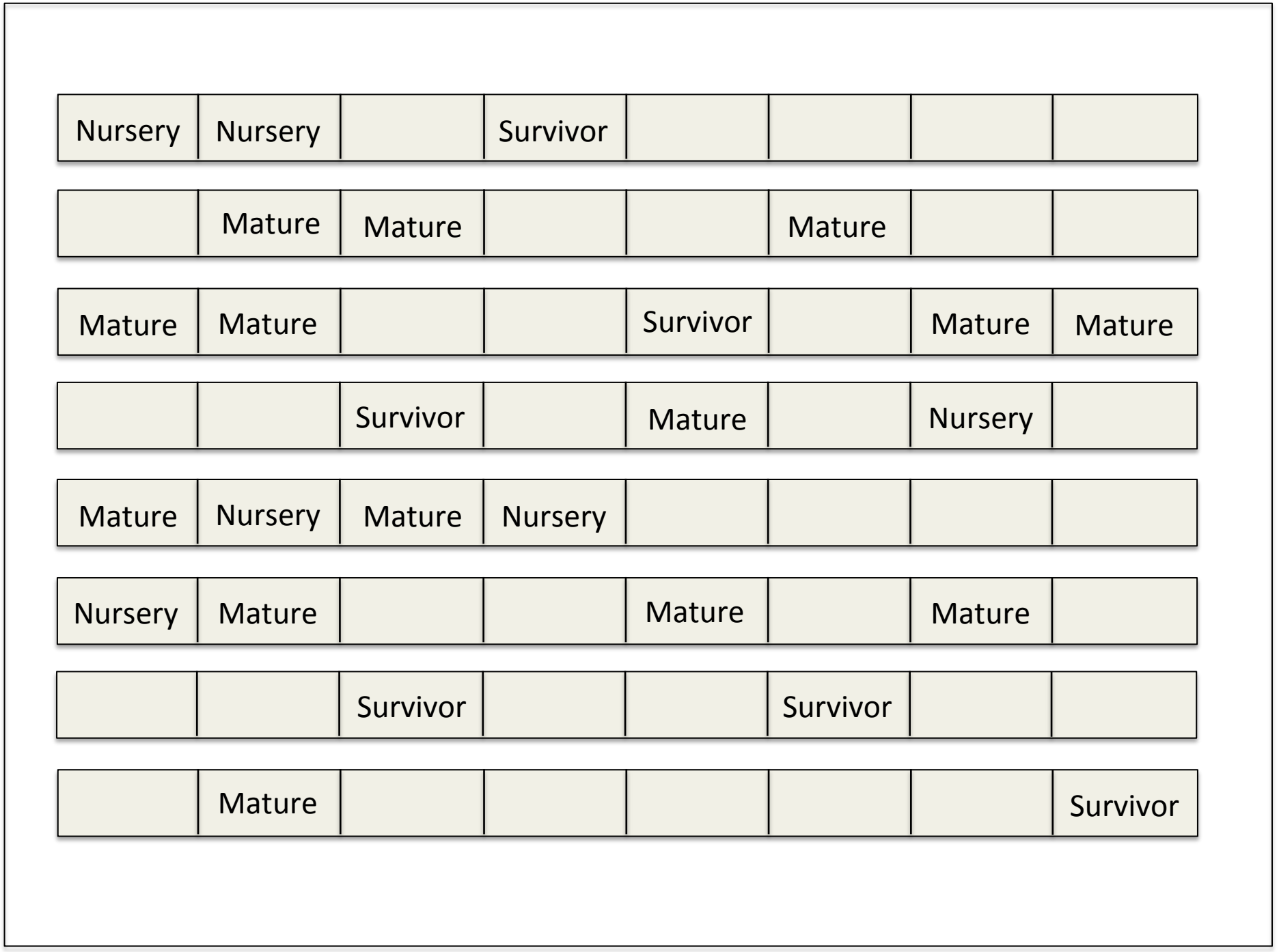
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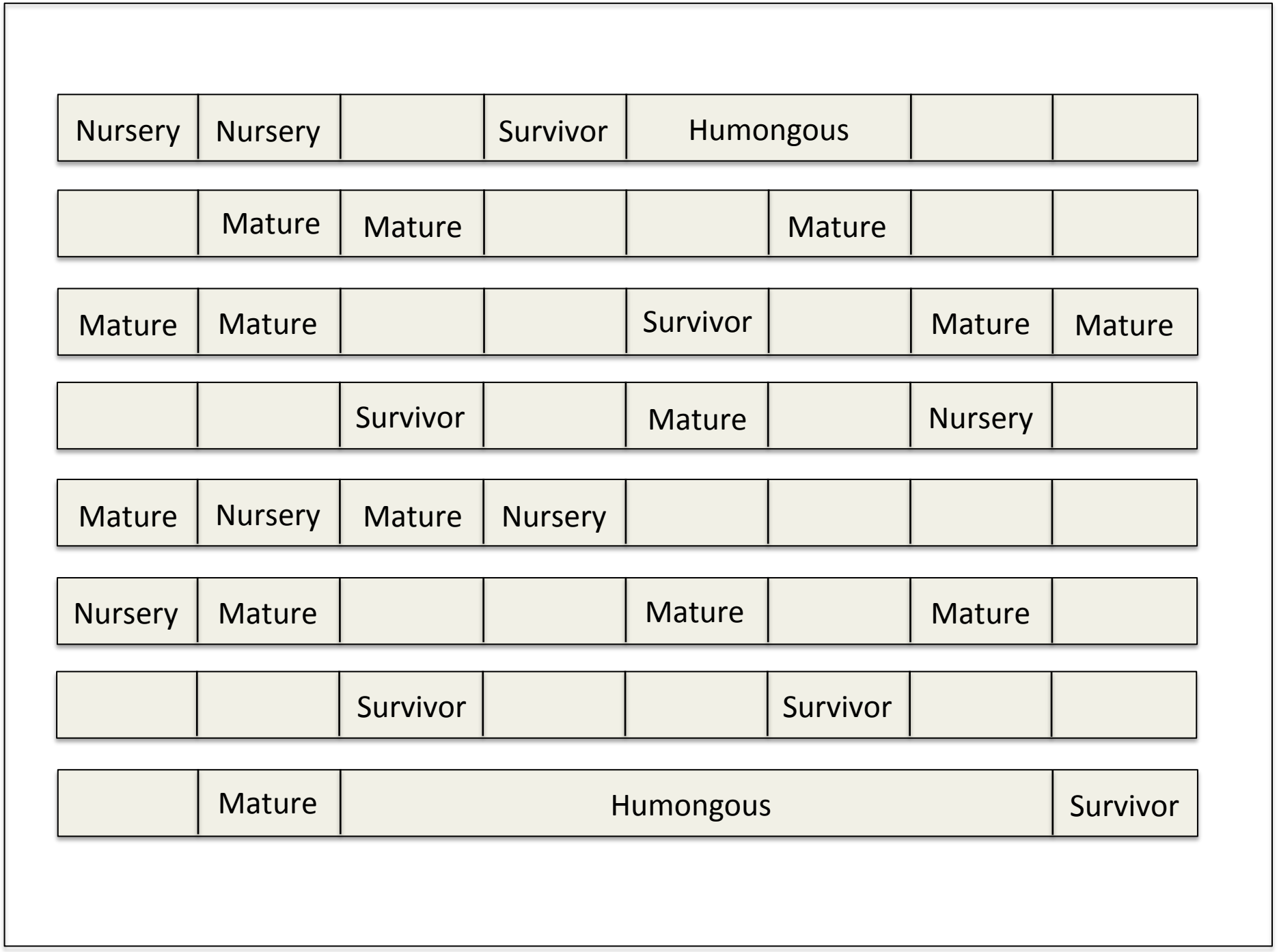
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Remembered Sets

- Maintain remembered sets for each region
  - Track references to that region from outside
  - Don't track internal references
- Maintain set using a write barrier
  - Use block alignment to generate region ID
  - Simple shift operation
- Remembered sets give estimate of live data

Minor GC

- Parallel stop-the-world copying collection
- Promote all live young objects
  - Move objects from nursery to the survivor regions
  - Move objects from the survivor to the mature
- Don't evacuate all young objects at once
  - Determine nursery regions by pause time
  - Determine survivor regions by garbage ratio estimates

Concurrent Marking

- Initial marking to scan the root set
  - Requires that threads be stopped
  - Piggy-backs on a minor GC pause
- Concurrent marking across the heap
  - Uses incremental update
- Remark phase to complete incremental update
  - Stops the world

Cleanup Phase

- After mark phase we know all live objects
  - Remembered sets aggregate the information
- We can explicitly target regions with more garbage
  - Minimize copy overhead
  - Reclaim more garbage in a bounded time
- In many cases a region is entirely garbage
  - Remember the train algorithm

Evacuation

- Final part of major collection
- Iterate over regions selected for copying
  - Copy all live objects to an empty region
  - Highly parallel
  - Uses a form of TLAB to minimize contention
- Number of regions copied can be tuned
  - Trade-off throughput for pause time

BENCHMARKING

Benchmarking

- Benchmarks are big business
  - Drive adoption of a given platform
  - Encourage investment in technology
- They provide great ammunition for flame wars
  - What would Slashdot be without benchmarks?
- Benchmarks are almost all worthless

Apples to Apples Comparison

- An ideal benchmark compares like for like
  - Single application running on different JVMs
  - Identical hardware and software platforms
  - Running in single-user mode
  - Networking and other interrupts turned off
- A good experiment uses many runs
  - Average over many (n > 30) iterations
  - Take standard deviation, confidence intervals, etc

Micro Benchmarks

- Small kernels of code that test a given operation
- Generally implemented as a tight loop
  - Allocations per second
  - Monitor acquisitions and releases
  - Floating point operations per second
- Very hard to make a micro benchmark interesting

```
public class SquareRoot {

    public static void main(final String[] args) {
        int iterations = Integer.parseInt(args[0]);
        long start = System.currentTimeMillis();

        for (int i = 0; i < iterations; i++) {
            Math.sqrt((double) i);
        }

        long end = System.currentTimeMillis();

        System.out.println("Time: " + (end - start));
    }

}
```

JIT Compilation

- The JIT is designed to defeat microbenchmarks
  - Dead loop elimination
  - Constant folding
  - Escape analysis
- Many microbenchmarks measure startup costs
  - Code runs in interpreted mode for a time
  - JIT compiler is triggered
  - Benchmark behavior changes completely

Phase Behavior

- Native code tends to start at full speed
  - Compilation happens ahead of time
- Managed runtimes take time to get started
  - Startup time required to initialize the VM
  - Initially run in interpreted mode
  - JIT compilation kicks in after a while
  - Runs at full speed after compilation period

Macro Benchmarks

- Aim to emulate real-world applications
- Various SPEC benchmark suites
  - SPECjbb2000, 2008, 2013
  - SPECjvm98, 2008
- DaCapo benchmark suite
  - Targets interesting memory management behavior
- Java Linpack
  - Java version of popular floating point benchmark

Macro Benchmark Benefits

- More likely to reflect real applications
  - Run for a reasonably long time
  - Workloads can be analyzed and considered
  - More often designed to account for phase behavior
- More varied operations
  - Don't obsess over a single part of the VM
  - Use a mix of custom and library code

Macro Benchmark Issues

- May not test what you think
  - Applications sometimes spend time in strange places
- Repetitive workloads
  - Increase run time by doing the same thing again
- Macro benchmark suites become obsolete
  - SpecJVM98 now runs in seconds, not minutes
- Limited number of benchmark suites
  - VM vendors can target and optimize for them

GC Benchmarking

- GC is notoriously hard to benchmark
  - Synthetic applications behave differently from real
  - Benchmark times too short for interesting behavior
- Micro benchmarks focus on the nursery
  - Generate lots of small, similar objects
  - Create occasional large, long-lived objects
- Many macro benchmarks never trigger full GC
  - Well-tuned system can run for surprisingly long

Java Benchmarking Advice

- Include a sufficient warm-up phase
  - Get past the startup overhead
  - Run the workload for a while to let the JIT work
- Measure steady-state behavior
  - Assume that Java applications run for a long time
- Avoids benchmarks targeting Java's weaknesses
  - By focusing on Java's strengths?

General Benchmarking Thoughts

- The only important benchmark is your application
  - Make sure that your own code runs well
  - Target the right platform for the job
- Benchmarking shows that any application can be tuned
  - Use that to your advantage
  - Profile your realistic workloads
  - Optimize the important parts
- Try out your application with different VM settings
  - Or even running on different JVMs

MULTITENANT VM

VM Overhead

- The Java VM is a heavyweight system
  - VM internal data structures and mechanisms
  - Full compiler implementation
- Many applications use the same libraries
  - Collections, Spring, XML processing, etc
- Every Java application incurs the same overhead

Multitenancy

- Ideally, multiple programs could share the VM
  - Single VM startup pause
  - Compile common classes once
- Classloading provides limited sharing
  - Doesn't give the illusion of a private VM
  - Class loading semantics decrease potential sharing
  - Difficulty in terminating the program
  - Semantics for JVMTI

Multi-Tasking Virtual Machine

- Project Barcelona in Sun labs (pre-Oracle)
- Introduced isolates to Java
  - Defined an isolate as a sub-process within a VM
  - Isolates share no state with other isolates in the system
  - Each isolate appears to be its own VM
- Allowed for aggressive optimization across isolates
  - Transparent to the developer

MVMs Today

- Specification is available to implementers
  - JSR 121: Application Isolation API
- Two reference implementations from Sun
  - MVM, MVM2
- Interest died down after the initial work
  - Machine-level virtualization made it less interesting
- Interest appears to be picking back up now
  - Vendors interested in PaaS cloud offerings

VM SHUTDOWN

Shutdown Modes

- Ideally, the JVM always shuts down gracefully
  - May happen if the VM encounters an internal bug
- VM can abruptly halt
  - Receives a SIGKILL or TerminateProcess interrupt
  - The host machine crashes
- Graceful shutdown happens in several cases
  - Final non-daemon thread exits
  - VM receives an external interrupt signal
- Shutdown involves several phases

Shutdown Hooks

- Program designates work during termination
  - Flush buffers
  - Close connections
- Hook is specified as an un-started Thread
  - Recommendation for defensive programming
  - Expectation that work should not take long
- Hooks run in any order at shutdown time

Forcing Finalization

- VM option forces all finalizers to run on exit
  - Gets around the limitation on whether finalizers run
- Finalizers can contain arbitrary code
  - Developers may not have considered shutdown
  - Code could deadlock or slow shutdown
- May be many objects to finalize
  - Large heap sizes imply more objects to finalize

JVM Exit Preparation Step

- Any JVM shutdown hooks run after Java code
  - Delete-on-exit files
- Clean up most VM structures and threads
  - Profiler, signal thread, GC threads
- Notify JVMTI agents
  - VM death events sent to all registered agents
- Native code may still be running
  - Set a flag in the JNI thread environment

Final Shutdown

- Terminate any remaining Java threads
  - Daemon or shutdown hooks
- Bookkeeping tasks for any Java thread
  - Release JNI reference handles
  - Mark thread as terminated
- Terminate the VMThread
  - Bring any threads to a VM safepoint
  - Stop JIT compiler threads
- Return control to the OS

METACIRCULARITY

Self-Hosting

- A compiler is just a regular computer program
  - Takes source files as inputs
  - Produces executable code as output
- A self-hosting is one that can compile itself
  - Compiler written in the target language
- Chicken-and-egg problem
  - Interrupt the recursion with a bootstrap compiler

Metacircularity

- Special case of a self-hosting runtime
  - The language's own features optimize the runtime
- Both VM and application are optimized together
  - VM data structures managed by the GC
  - VM code passes through the JIT
- VM can to be written in a higher-level language
  - Use Java synchronization rather than pthreads

JIT Compilation

- Much of the VM implementation relies on the JIT
  - Compiles both the VM and the application
- The JIT is an metacircular JVM is written in Java
  - Which must be JIT compiled
- Same problem as self-hosted compilers
  - Solve in the same way
  - Create a small bootstrap VM
  - Bootstrap VM is used only to get the system running

Intrinsics

- Some required language features are unavailable
  - Low-level pointer access is the most obvious
- Remember JIT compiler intrinsics
  - JIT has a better implementation than the class file
  - Class file is ignored
- We can use intrinsics to implement new features
  - Intercept all calls to a given class or interface
  - JikesRVM uses the org.vmmagic package

Magic

- Magic package split into two parts
- Pragma annotations
  - Tell the compiler to change the method
  - Remove safepoints, control compilation, etc
- Intrinsic annotation
  - Tell the compiler to replace the entire method

Magic Intrinsics

- `org.jikesrvm.runtime.Magic` has method stubs
  - Directly access registers
  - Manipulate stack frames
  - Cast arbitrary bits to Java types
  - Pointer arithmetic
  - Atomic operations such as CAS and memory fences
- Method stubs just throw runtime exceptions
  - Really there for the javac compiler
  - JIT compiler recognizes calls and rewrites