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# Garbage Collection for General Graphs

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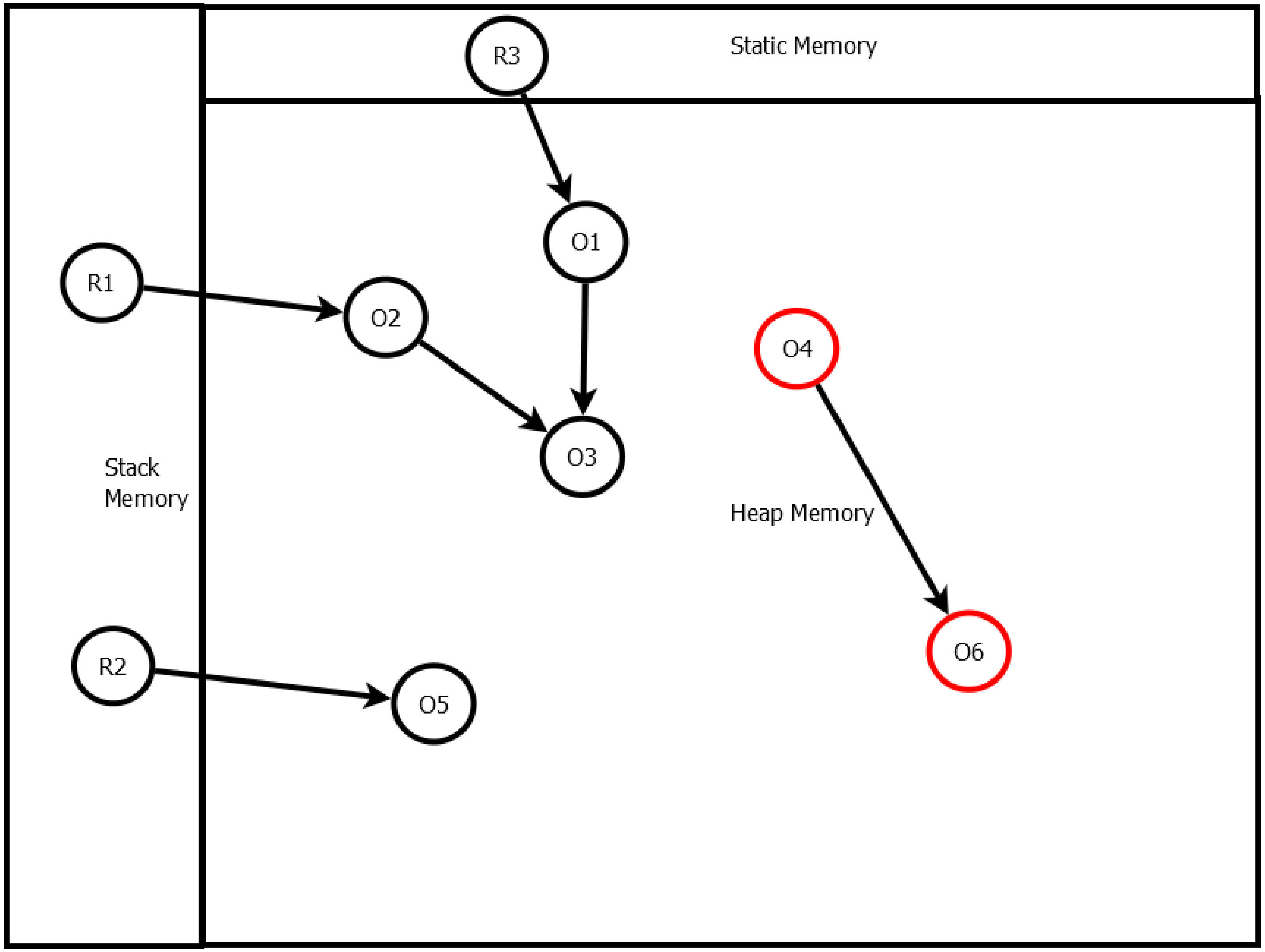
# Garbage Collection (GC)

- In heap memory, objects hold pointers/references/links to other objects in the heap.
- Stack variables and static variables hold references to objects in the heap. They are called roots ( R ).
- An object is said to be reachable / live if there is any path from a root to the object.
- Unreachable objects are called garbage and memory allocated for those objects can be reclaimed for future use.
- Garbage collection is the process of collecting unreachable objects in the heap.

# Garbage Collection (GC)



# How to collect garbage?

- Manual Memory Management (MMM) and Automatic Memory Management (GC).
- MMM is used by programmers who use languages with no managed run-time systems such as C/C++.
- GC is the thread that runs in the runtime systems(managed runtime systems) to automatically detect the garbage and reclaim them.
- GCs are widely available in various runtime systems including Java Virtual Machine, LISP, and Scheme systems.

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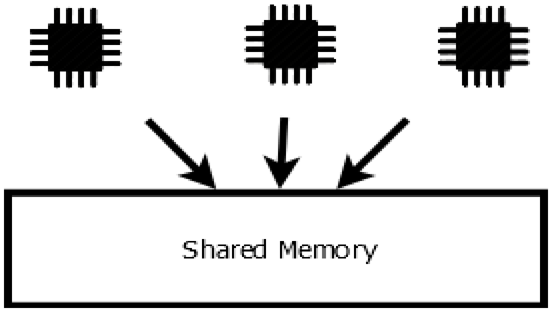
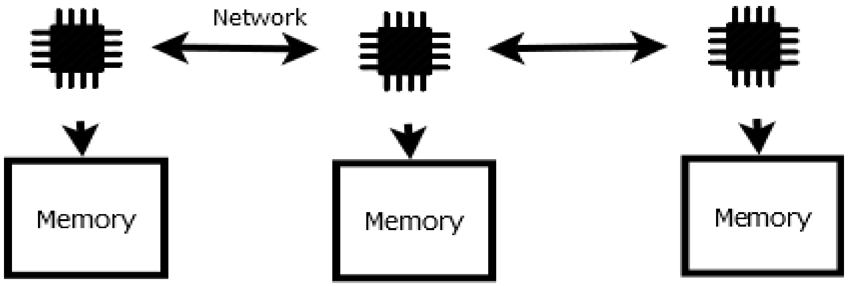
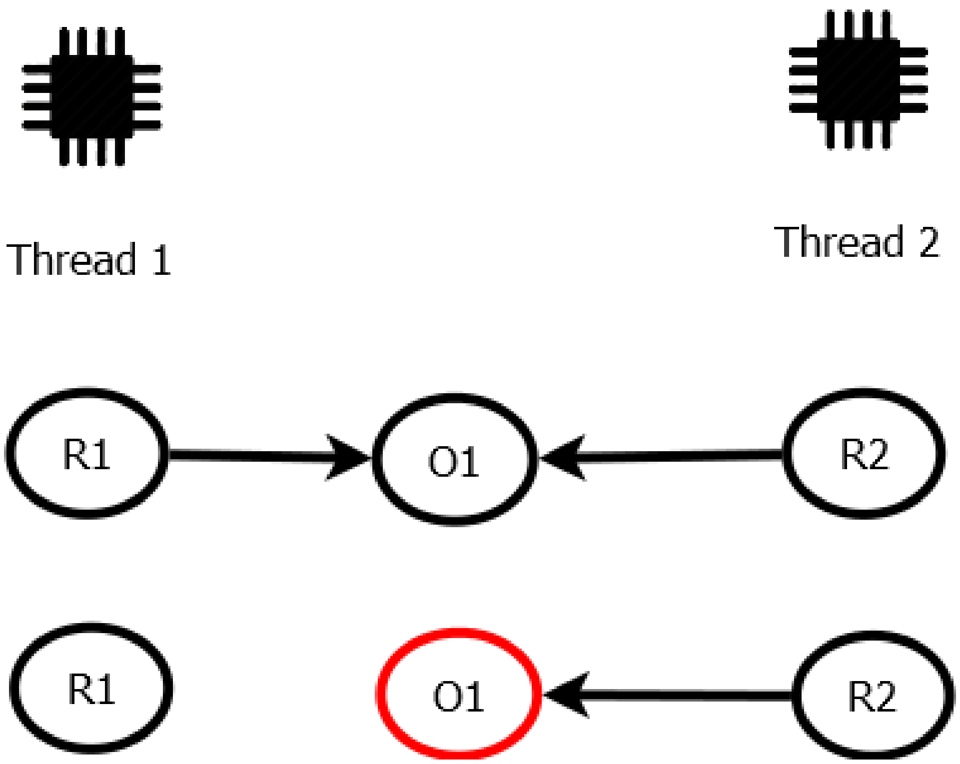
# Dangling Pointers

- Dangling pointer is a pointer that points to a deleted object.
- Some other object is allocated in the same address in the interim time.
- In MMM, simple reference counting based smart pointers can sometimes solve this problem in a concurrent programming environment.
- We focus on concurrent programs and their environments in this presentation.



# Dangling Pointers



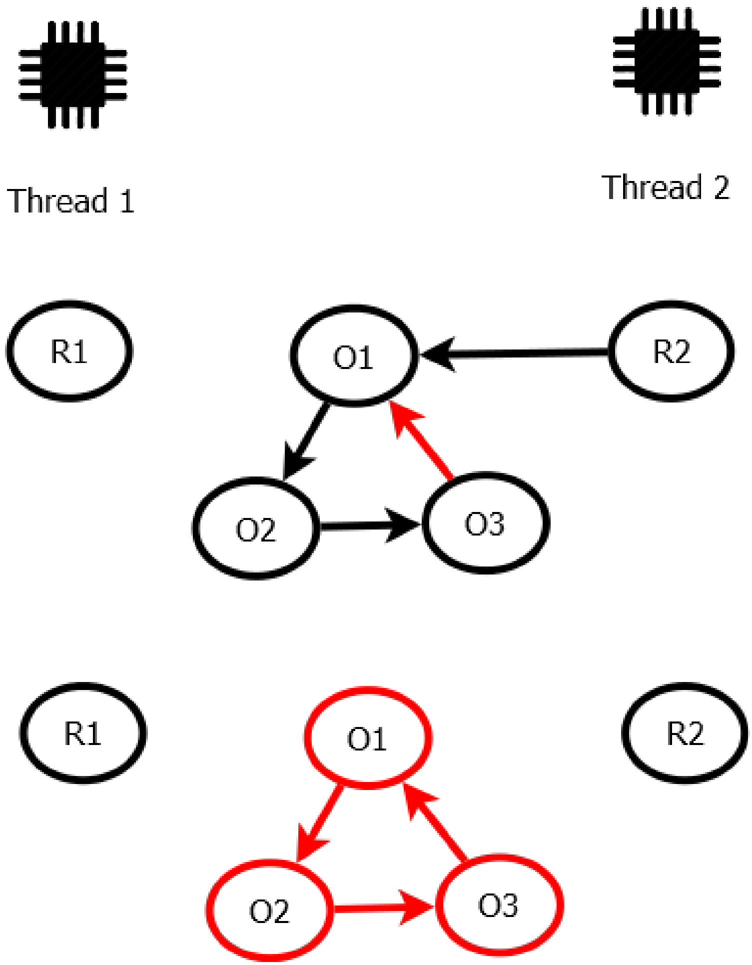
# Double-free Bugs (DFB)

- DFB is  pointer that points to a deleted object calls delete again.
- Some other object is allocated in the same address in the interim time and creates dangling pointers, or crashes.
- In MMM, simple reference counting based smart pointers can solve this problem in concurrent programming environment in an acyclic graph.
- Otherwise, timestamps are used in lock-free algorithms to avoid this problem (similar to ABA ).

# Memory Leak

- Objects in heap memory are not referenced by any roots but not deleted.
- Low memory utilization.
- Cycles in the heap cannot be reclaimed by smart pointers.

# Memory Leak



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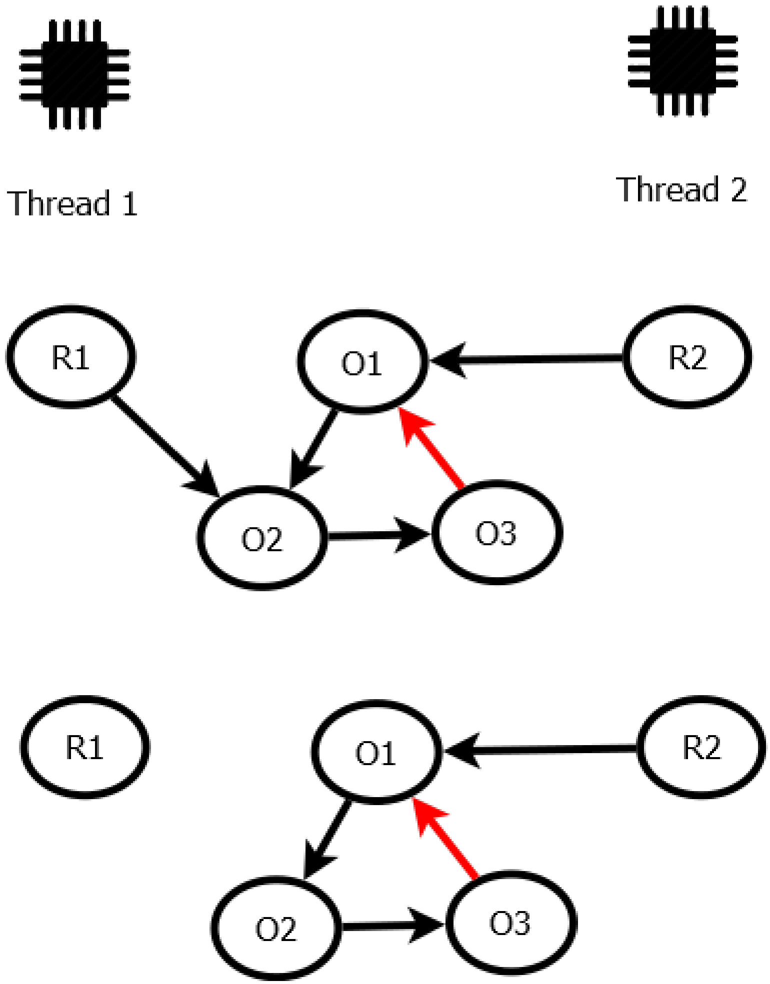

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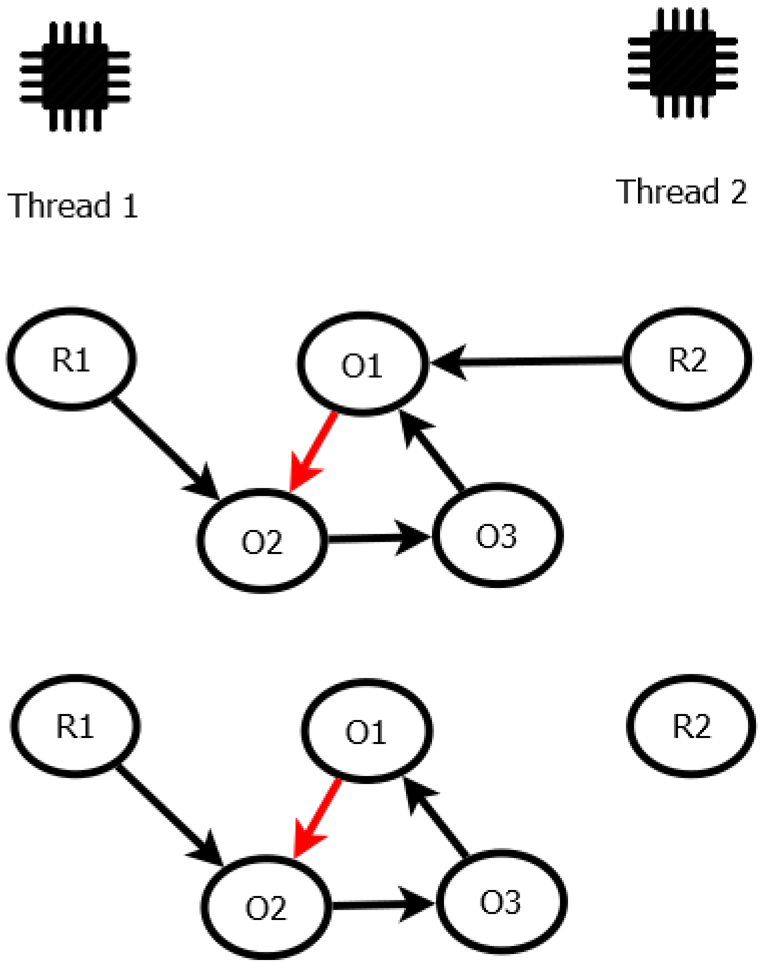
# Memory Leak



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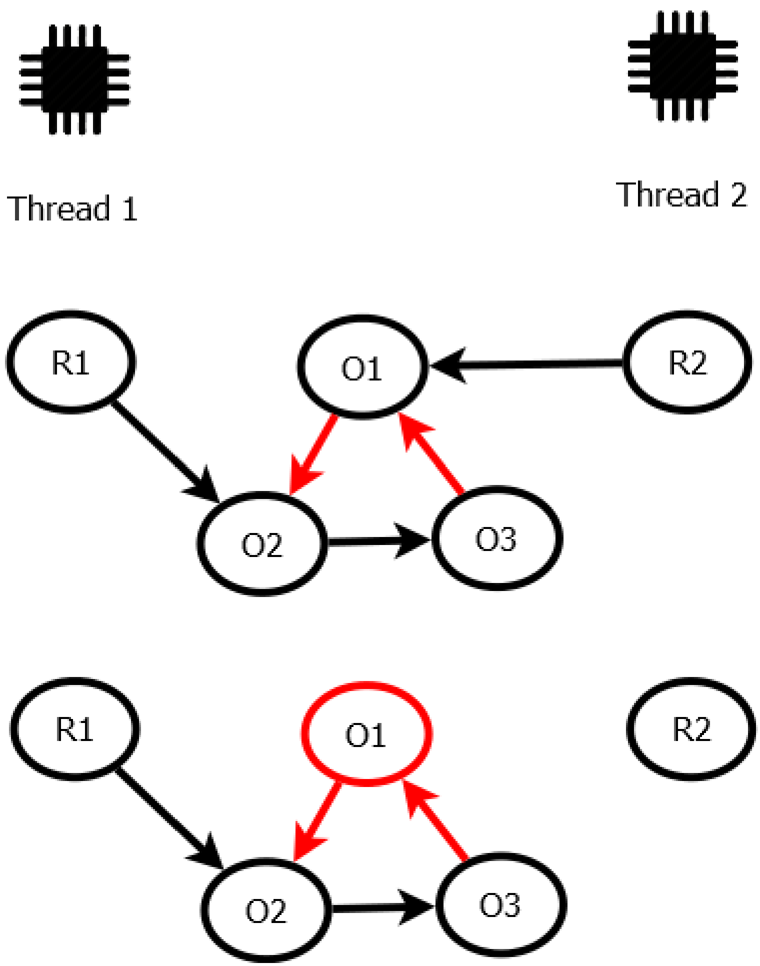
# Dangling Pointer



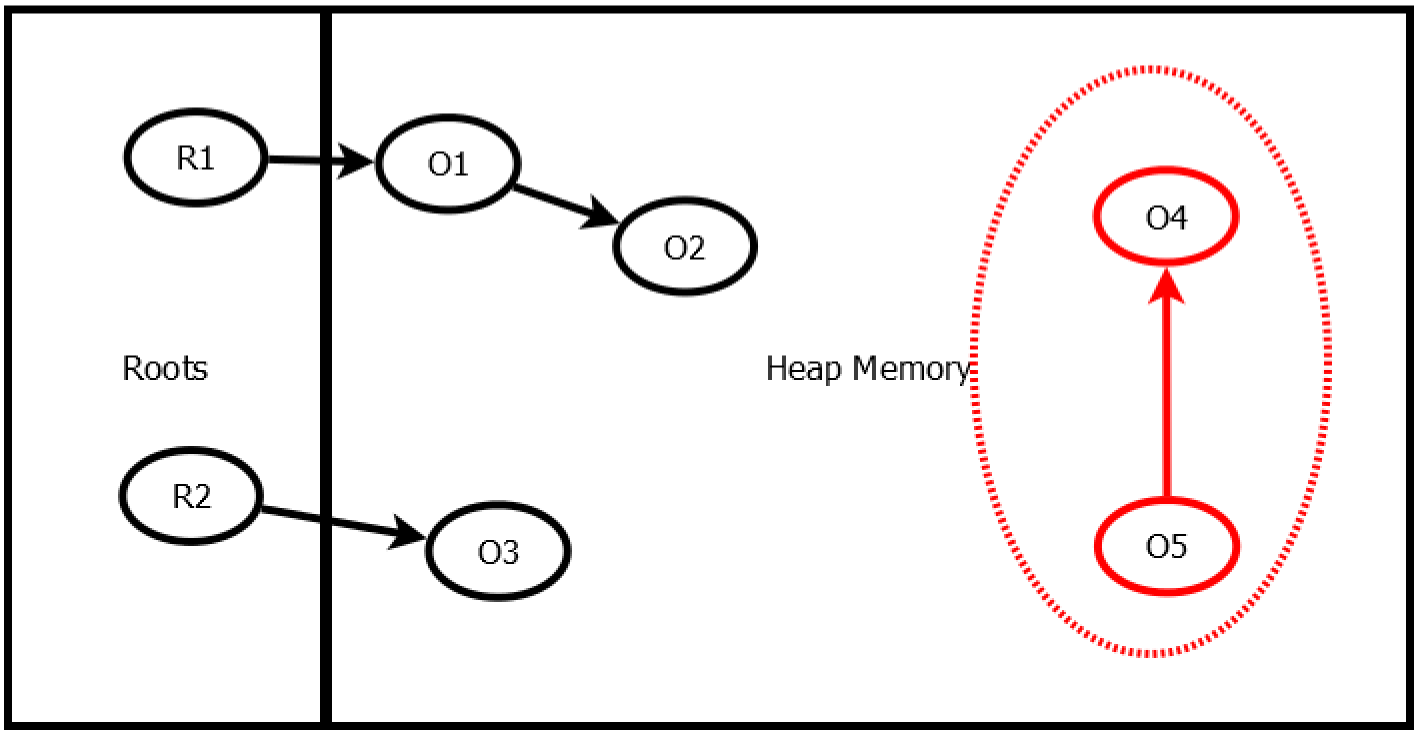
# Advantages of GC

- GC has the global knowledge solves the problem of dangling pointers, double-free bugs and memory leaks.
- Reduces number of lines of code to write.
- AHA! Boehm and Spertus announced that in the next C++ standard, GC can be expected!
- Commercial Software Development research claims GC reduces development cost. [Butters, 2007]
- Useful for distributed object stores, parallel and distributed programming languages, distributed databases, and WWW.

# Mark-Sweep

- When the amount of memory consumed reached its threshold, the collector starts marking the nodes reachable from the roots.
- Mark and Sweep only needs one bit and can be easily made concurrent.
- Garbage cannot be collected promptly.
- The whole allocated heap is traversed for each collection as they first traverse all the live nodes and then they traverse all the dead nodes to delete.

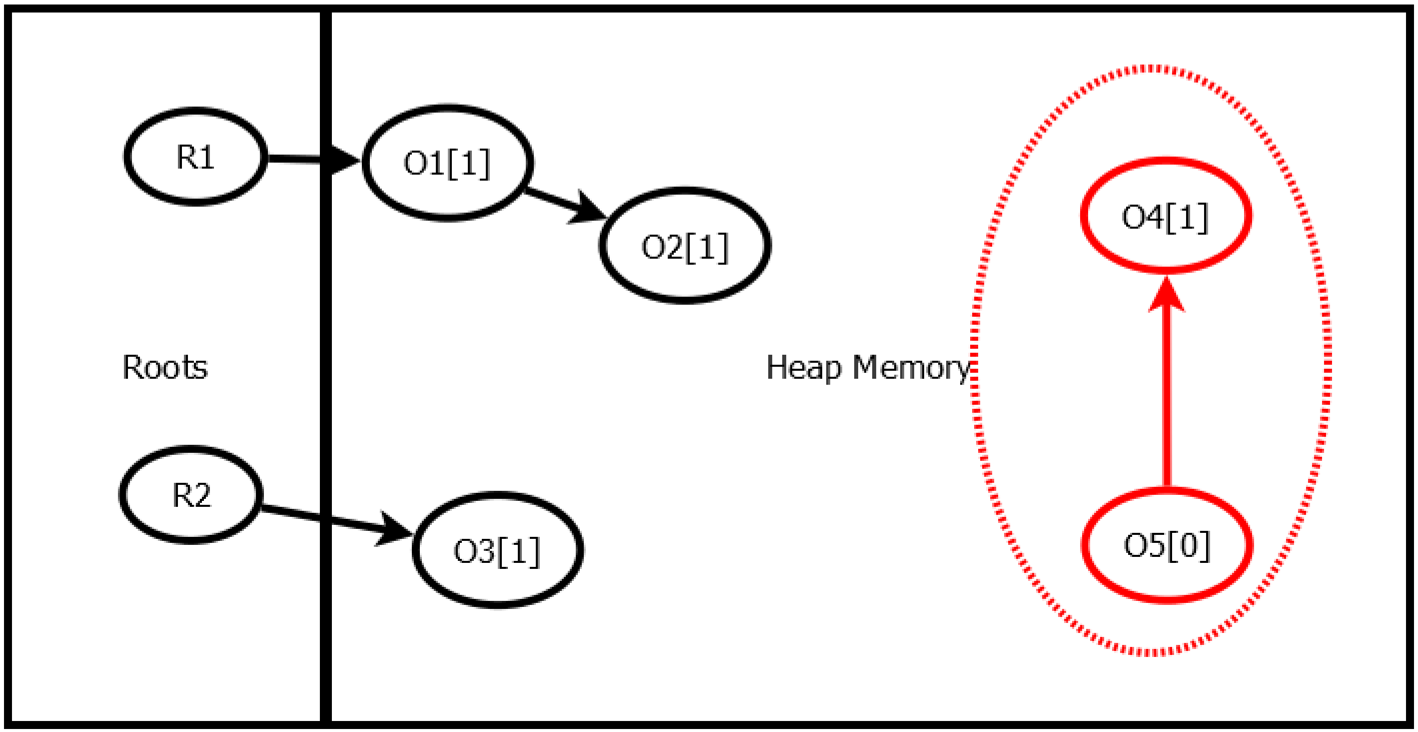
# Mark-Sweep



# Reference Counting (RC)

- Each object has a RC that denotes how many incoming references it has.
- When an object has zero RC, it is garbage.
- The method cannot delete cyclic garbage as all cyclic garbage nodes have positive RC.
- Apart from the inability to detect cyclic garbage, reference counts have to be updated for object when new reference is made or deleted.

# Reference Counting



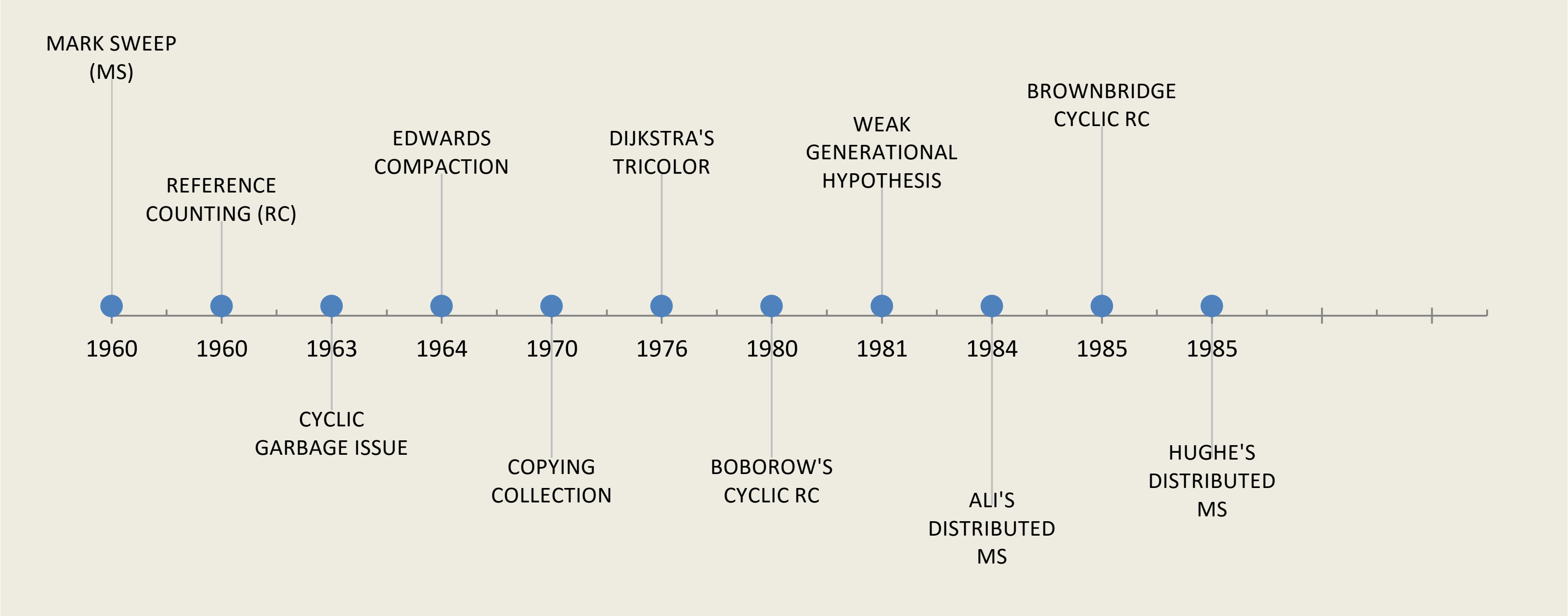
# Proposed Hypothesis

- Concurrent GC (Low Pause Time)
- Multi-collector GC (Parallel and High Throughput)
- No global Synchronization (High Throughput)
- Locality-based GC (High Throughput)
- Scalable
- Prompt
- Safe
- Complete

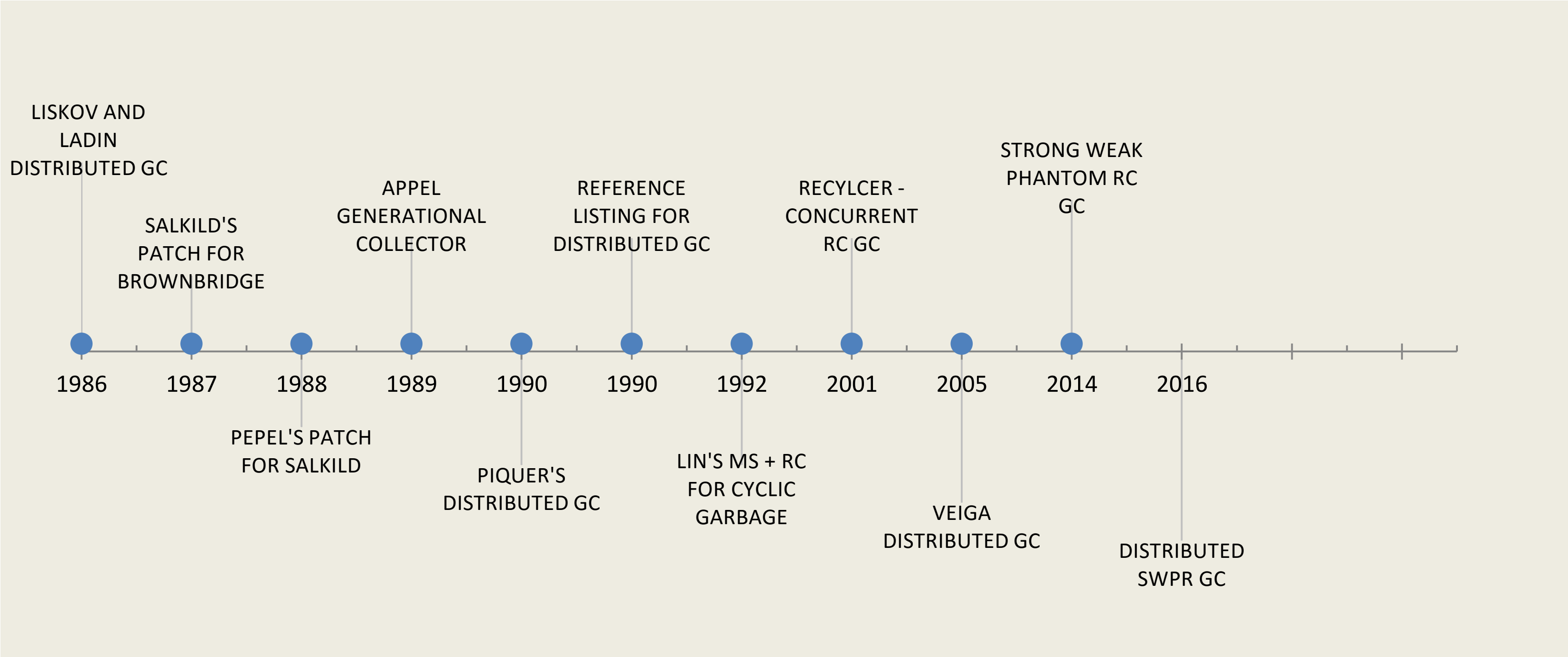
# Literature Review

| Name | C | MCA | GS | Locality | Scalable | Safe | Complete | Prompt | S/D |
|---|---|---|---|---|---|---|---|---|---|
| Mark Sweep | Yes | Yes | Yes | No | No | Yes | Yes | No | S & D |
| Reference Counting | Yes | No | No | Yes | No | Yes | No | Yes | S |
| Cyclic Reference Counting | Yes | No | No | Yes | No | Yes | Yes | Yes | S |
| Generational | Yes | No | Yes | No | No | Yes | Yes | No | S |
| Liskov | No | No | Yes | No | No | Yes | Yes | No | D |


# Literature Review



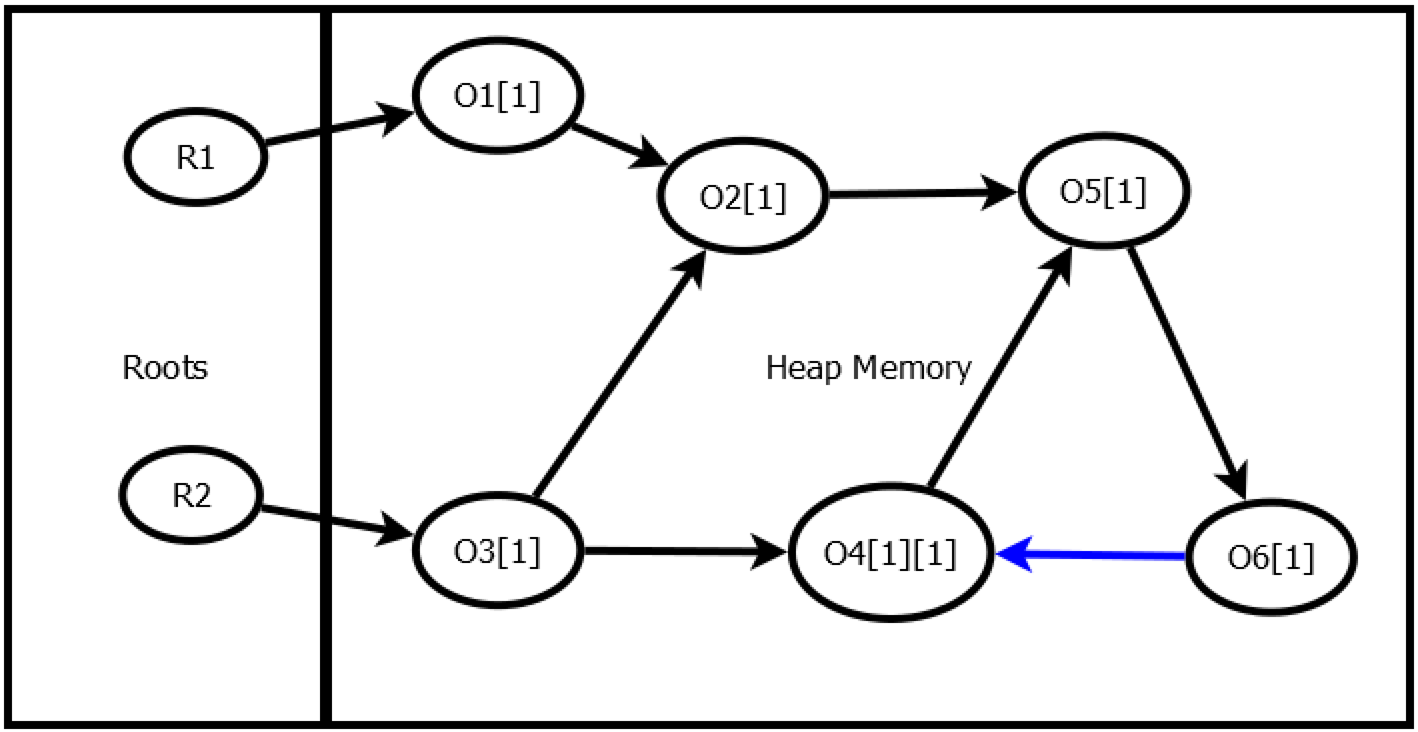
# Literature Review



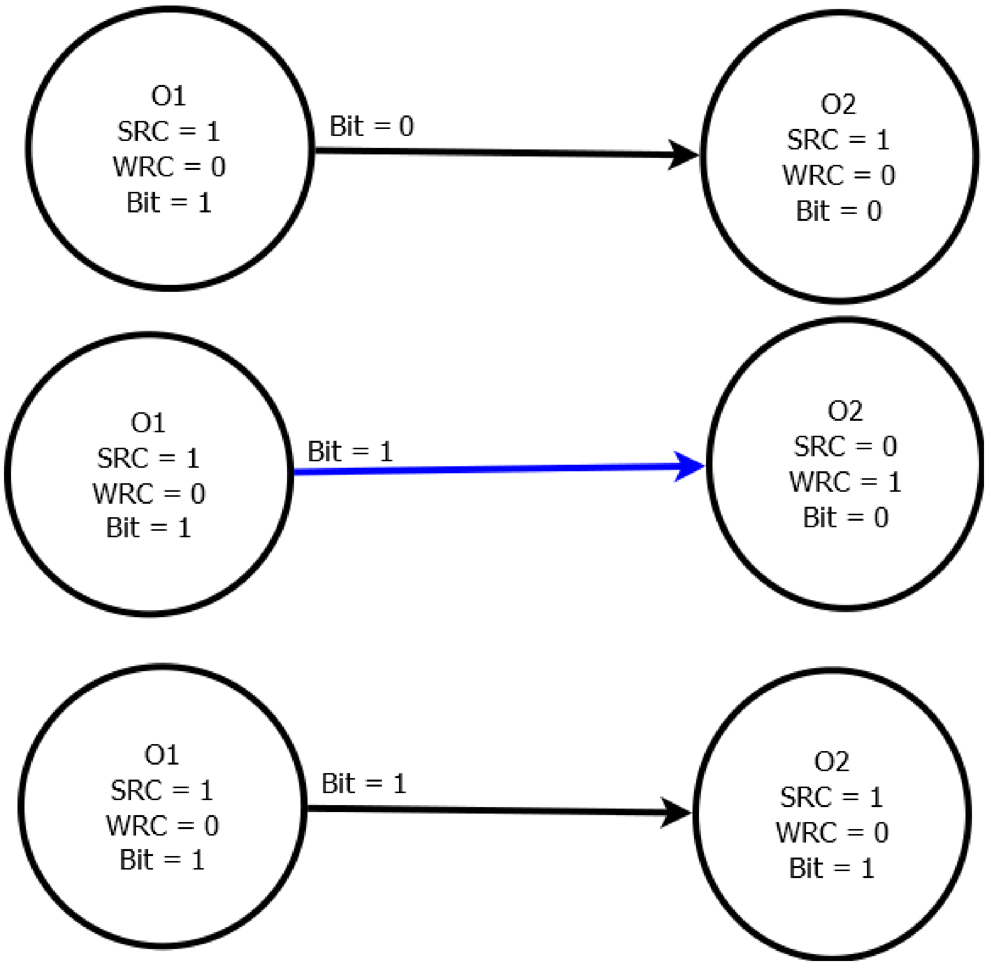
# Brownbridge Method

- RC and tracing technique to collect cyclic garbage.
- It uses two reference counts: Strong Reference Count (SRC) and Weak Reference Count (WRC).
- All live nodes have positive SRC.
- No strong cycles are allowed.
- When a reference is created to a node, if the target node already has outgoing references, it is considered a weak reference.

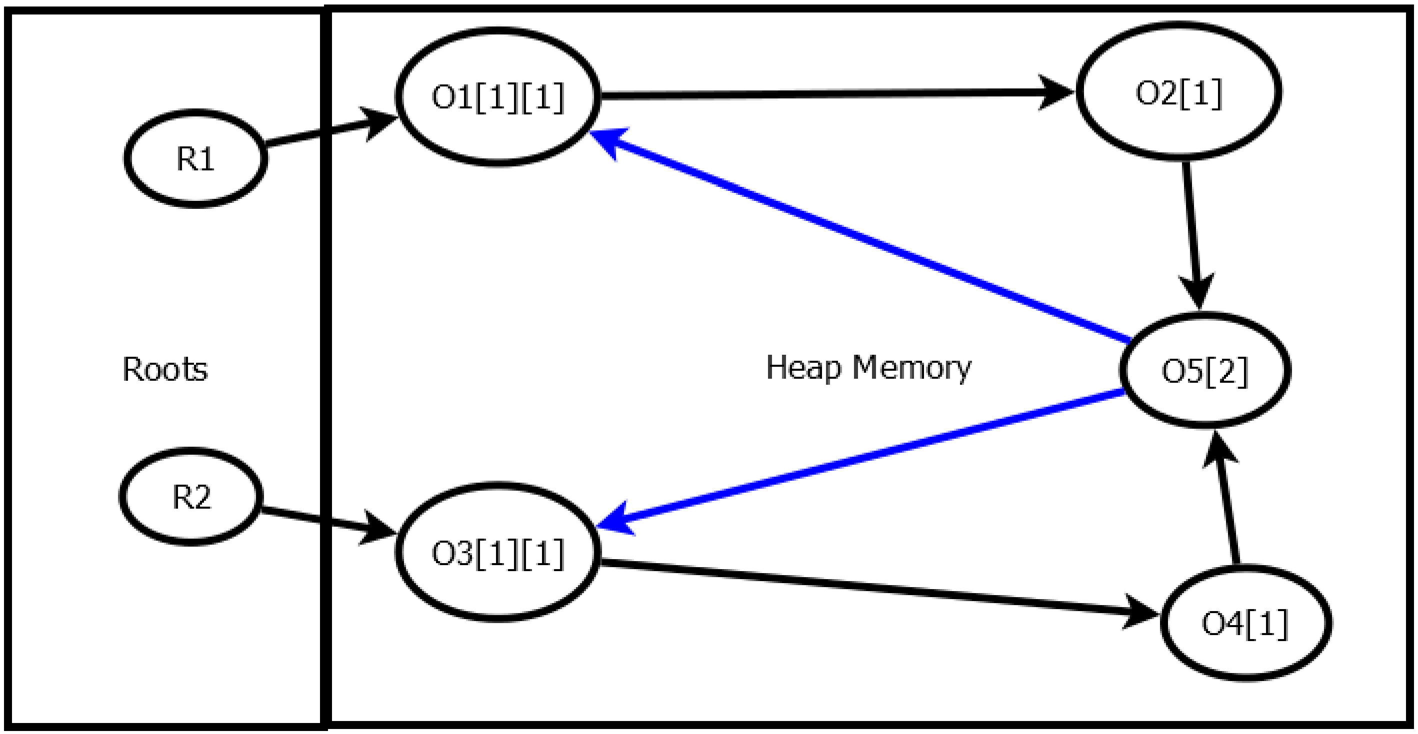
# Brownbridge Method



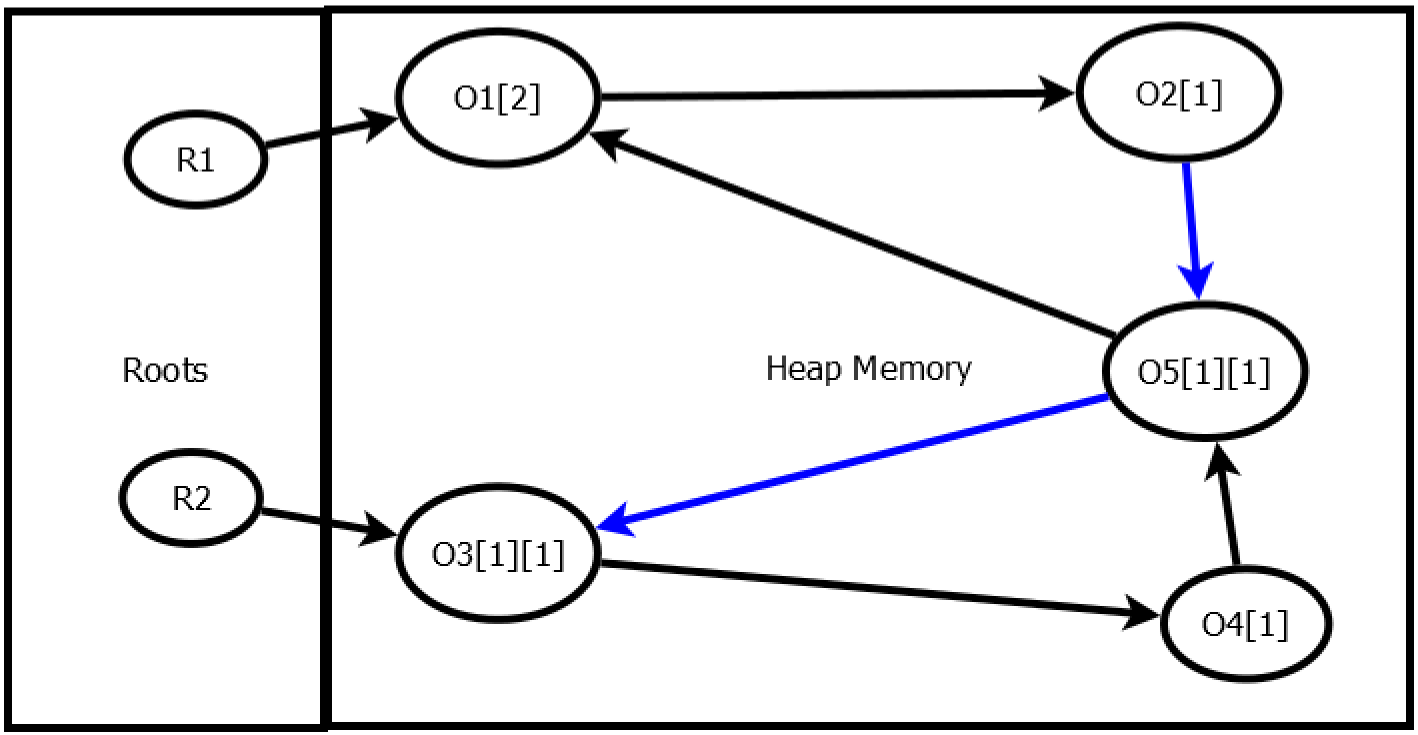
# Brownbridge Toggle



# Recover Case



# Premature Delete Case



# Salkild's and Pepel's Work

- Salkild eliminated the premature deletion but introduced non-termination in certain cases.
- Pepel improved Salkild’s work with the trade-off of exponential cleanup cost.
- Practically all of the attempts to correct the Brownbridge failed.

# Recycler

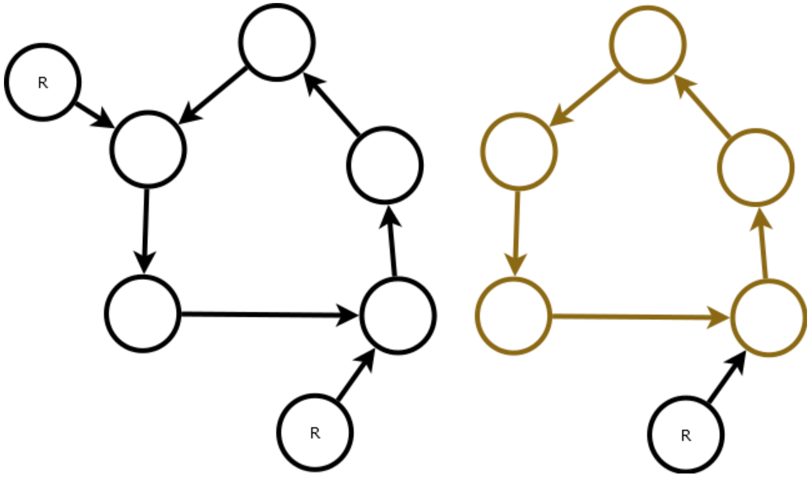
- David Bacon et al used the color algorithm to design a hybrid concurrent garbage collector.
- This method uses reference counting along with tracing to identify cyclic garbage and runs concurrently.
- It traces the entire connected graph and cannot be made to run parallel.
- Antony Hosking et al claims that Bacon’s method is incomplete and proof is insufficient.

# SWP

- Strong-Weak-Phantom(SWP) Reference Count GC.
- The idea is to create a path from a root to each live node through strong references and avoid creating cycles of strong reference by using weak references.
- **Strong Cycle Invariant :** No strong cycles will exist in the reference graph at any point in time.
- **Weak Heuristic** : All weak edges are not cycle closing edges.
- **Edge Label Heuristic**: An edge will be weak when the target node has outgoing edges at the time of creation.
- Phantom is a transient state that is used only in the cycle detection algorithm.

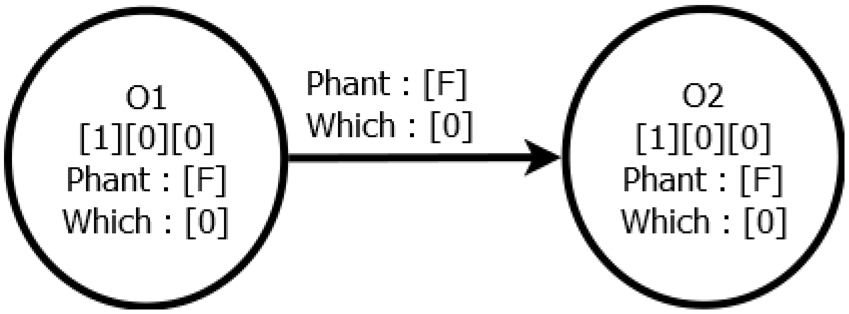
# SWP

| Counters | State |
|---|---|
| SRC > 0 | Live |
| SRC = 0 & WRC > 0 | Potential Cyclic Garbage |
| PRC > 0 | GC processing node |
| SRC = 0 & WRC = 0 & PRC = 0 | Garbage |



# SWP & Header

- Apart from reference counts, each node also has a which bit, phantomized flag, and an array of which bits for outgoing references.
- Process lists and request queues are used.



# Delete Edge

When a node loses its last strong reference:

if(WRC==0 && PRC==0)

start deleting the node and delete all outgoing edges

else if(WRC>0 )

convert all the incoming weak references to strong and phantomize outgoing edges

# Three phases

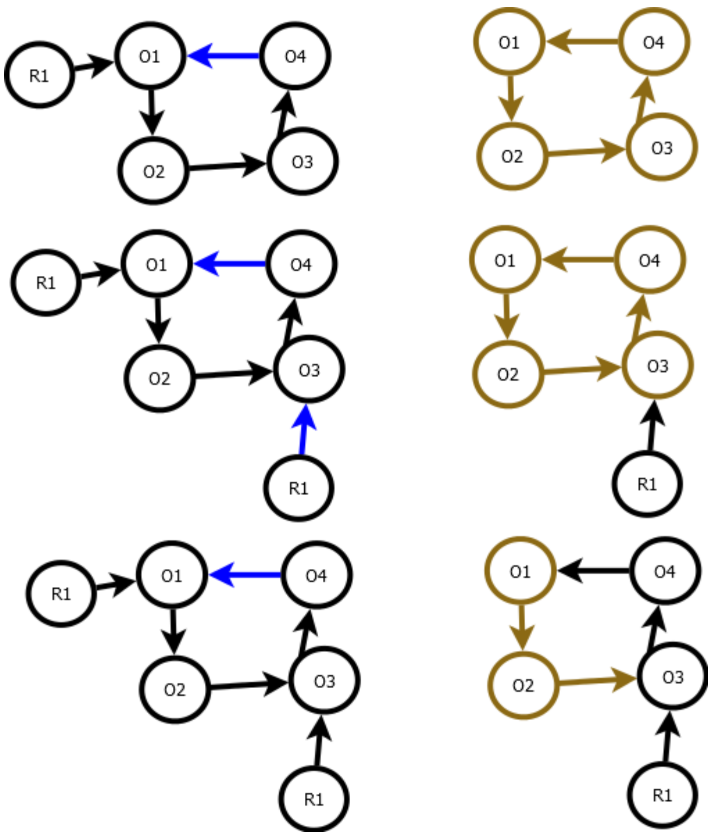
- Phantomize
- Recovery
- Cleanup

These three phases happen for each traversal initiated. Each collector thread maintains list of nodes it processed in each phase.

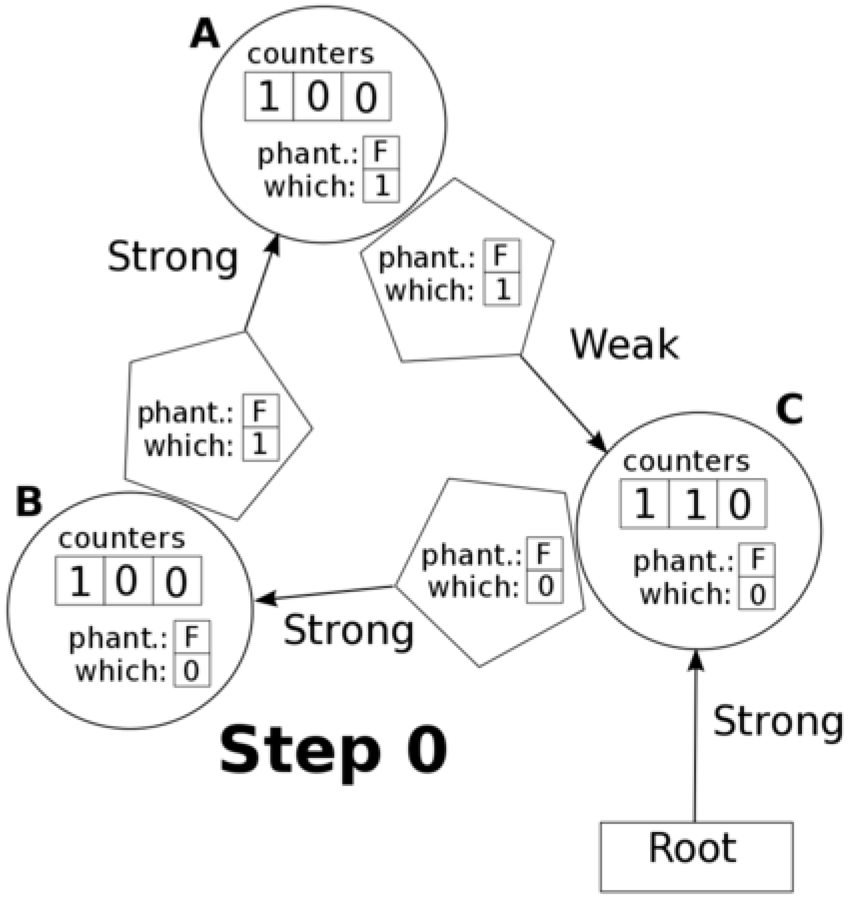
# Phantomization

- Decrement all internal references.
- Phantomization stops when it reaches a phantomized node, or a live node.
- Nodes toggle if any weak reference remain after phantomization.
- Phatomization propagates when any of the stop criteria is not met.

# Phantomization



# Simple Cycle Demo



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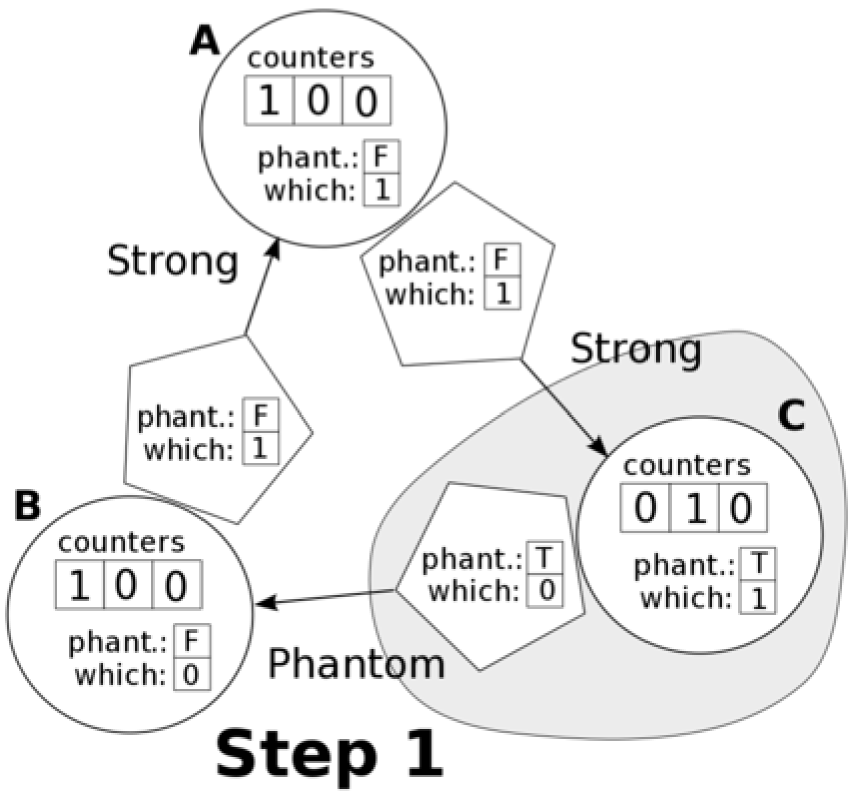

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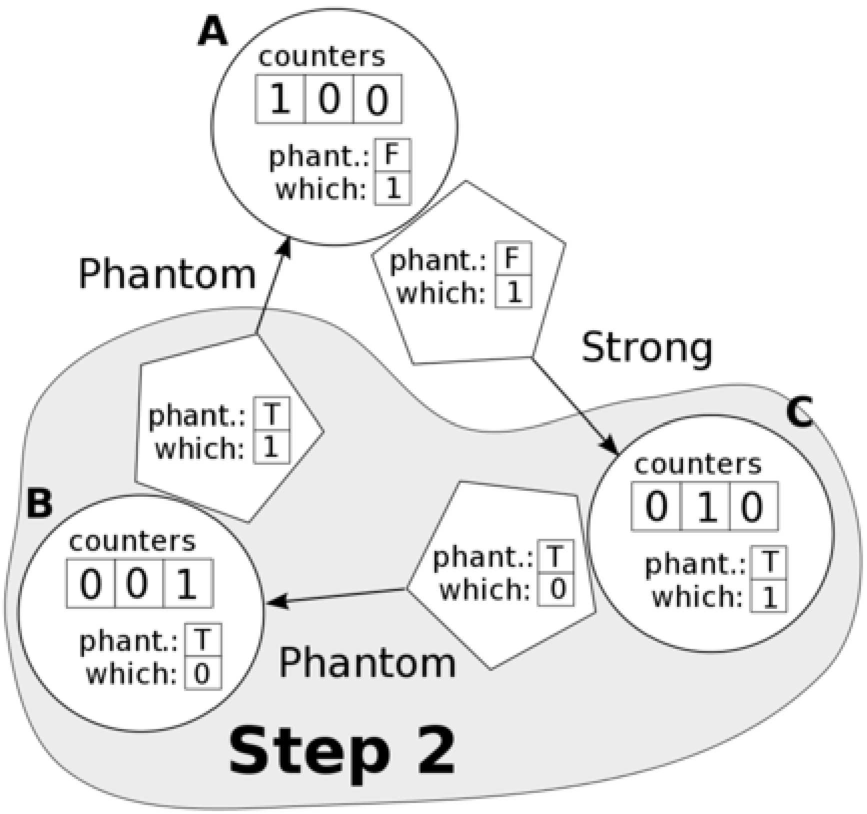

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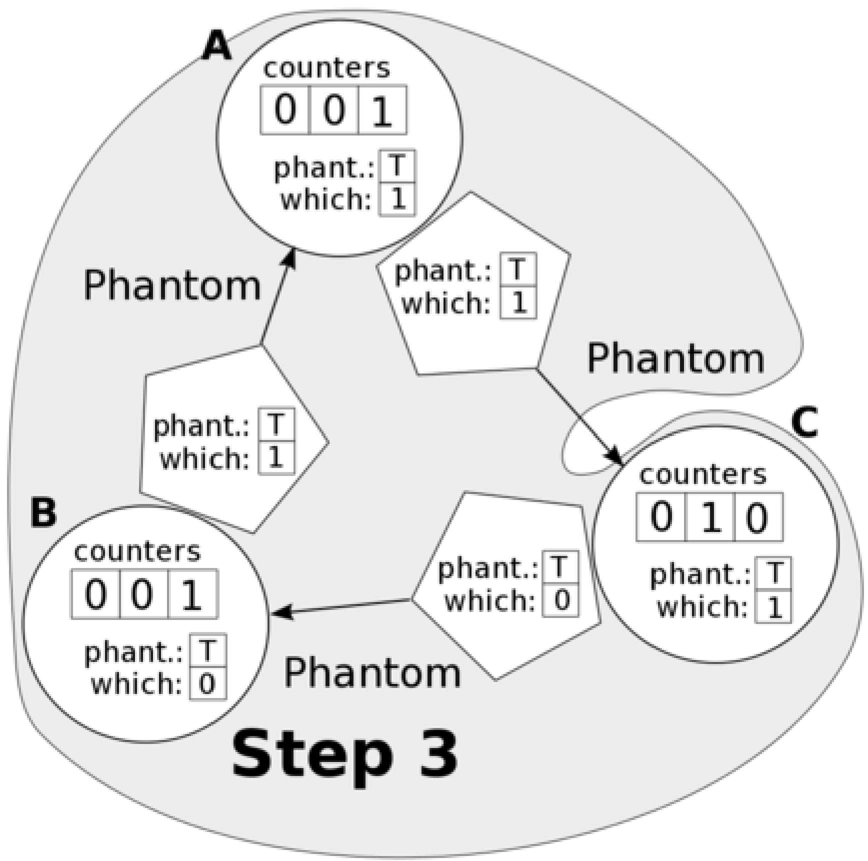
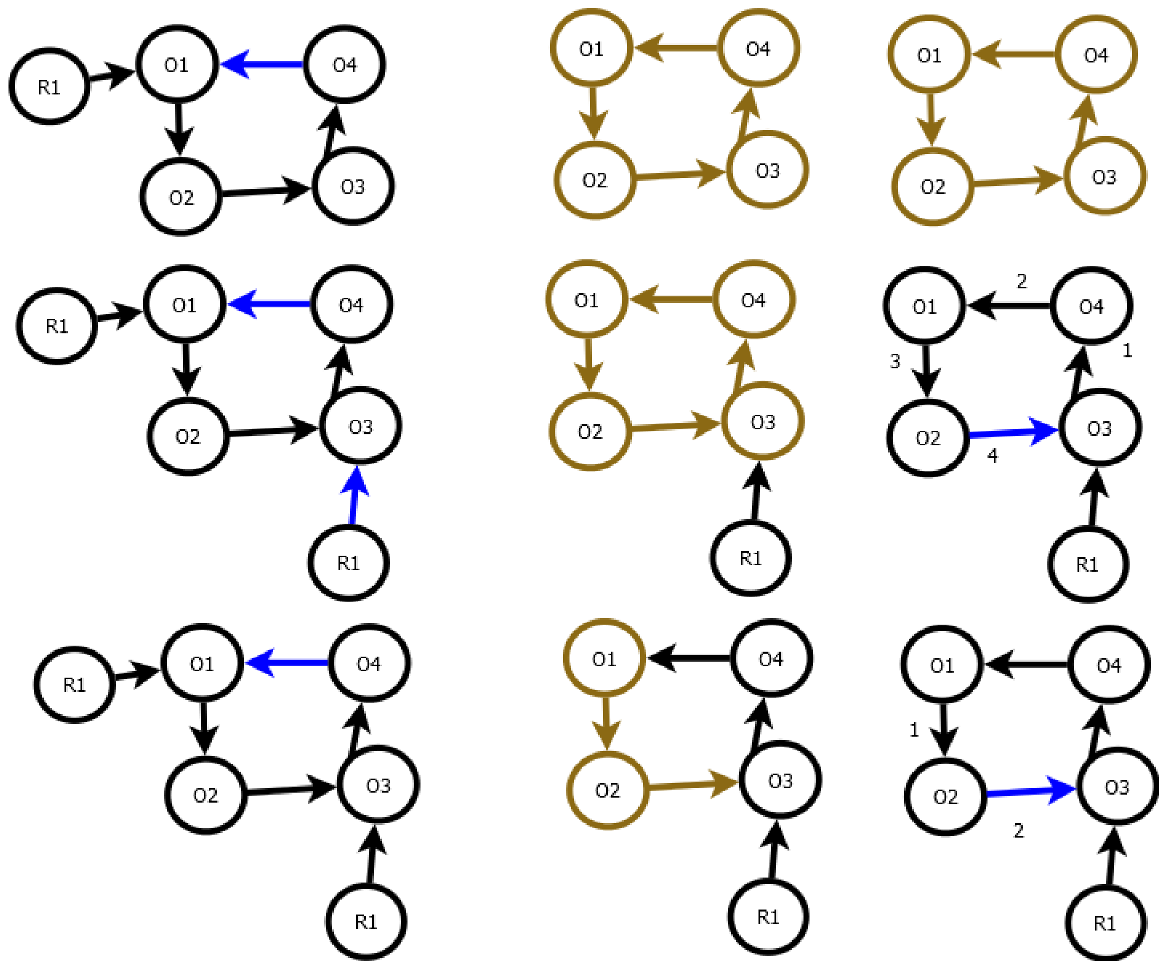


# Recovery

- If any external reference found, correct the graph to strong / weak graph
- Delete nodes from process list as they are recovered.
- Process starts by scanning all the process list contents and verifying if any of them has any strong references after phantomization.

# Recovery



# Concurrent and parallel Collector

- Atomic operations can be used to access RCs.
- SWP collection does not stop the application.
- Requests are queued.
- Collector thread processes the queue and starts the requested tasks.
- Collectors write their own id in collector id in parallel collector mode.
- When the collector visits a node with a different id, then they synchronize.

# Concurrent and parallel Collector

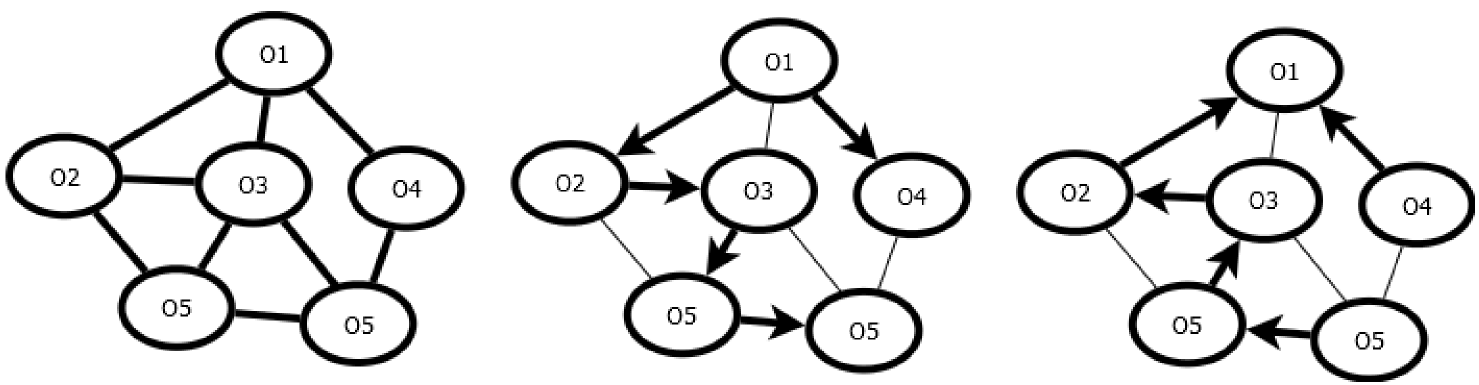
- **No Partition Principle** : When two or more collectors synchronize, they merges their lists of processed nodes and one of the collectors takes over the processing of those nodes.
- Parallel collector adds one more attribute to the object header.

# How SWP can be used?

- The SWP algorithm is directly applicable to shared memory systems.
- The SWP algorithm is also applicable to distributed system with centralized queues.
- Unlike other distributed GC systems which require the application to be halted, this one does not require it.
- Mobile actor based collectors do not require centralized queues and are directly applicable to the distributed systems with message size proportional to graph size.


# SWPR GC

- SWPR - > (Strong, Weak, Phantom, Recovery).
- Strong Cycle Invariant.
- Weak Heuristic.
- Distributed Termination Detection is used. (Parent attribute and Wait Count).
- SWPR is concurrent, multi-collector, locality-based, scalable, prompt, safe, complete, and functions without global synchronization.

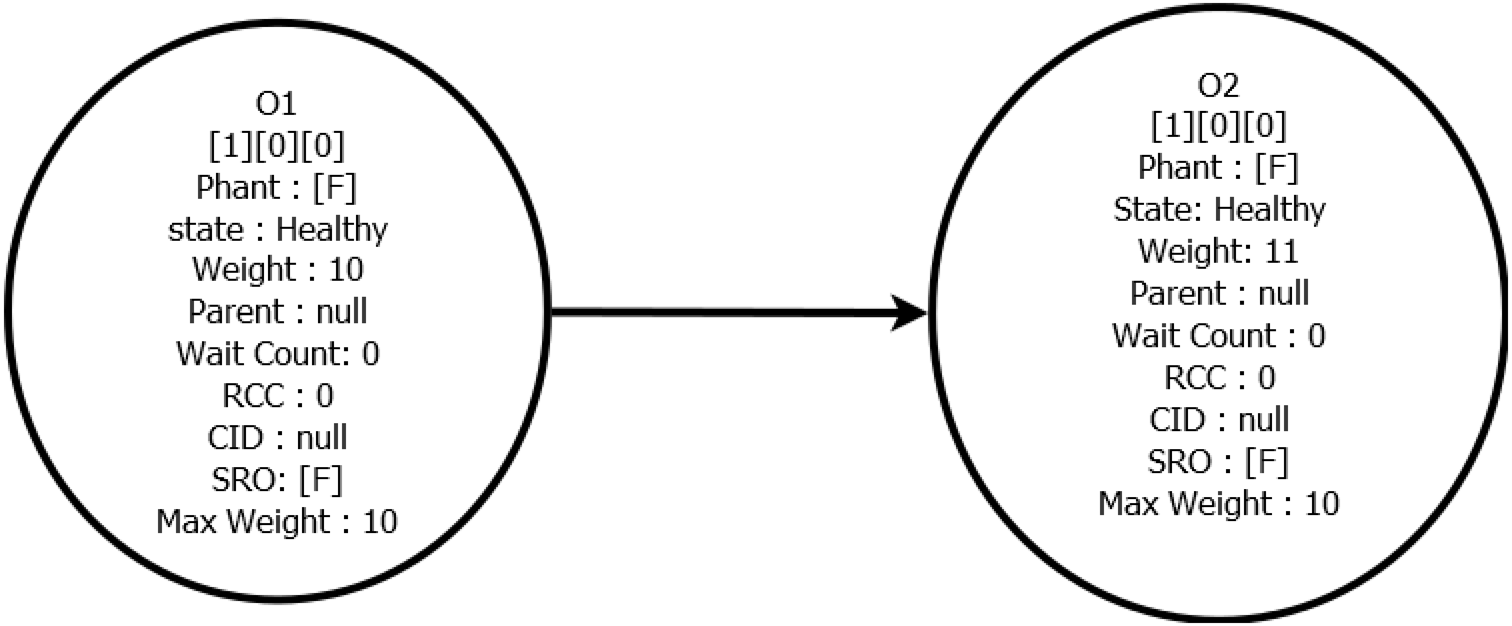


# Model

- Congest: $O(\log n)$ message size.
- No reference listings allowed.
- Garbage stable property.
- Nodes will only know out-neighbors.
- Nodes can send messages only to neighbors.
- Asynchronous network model.

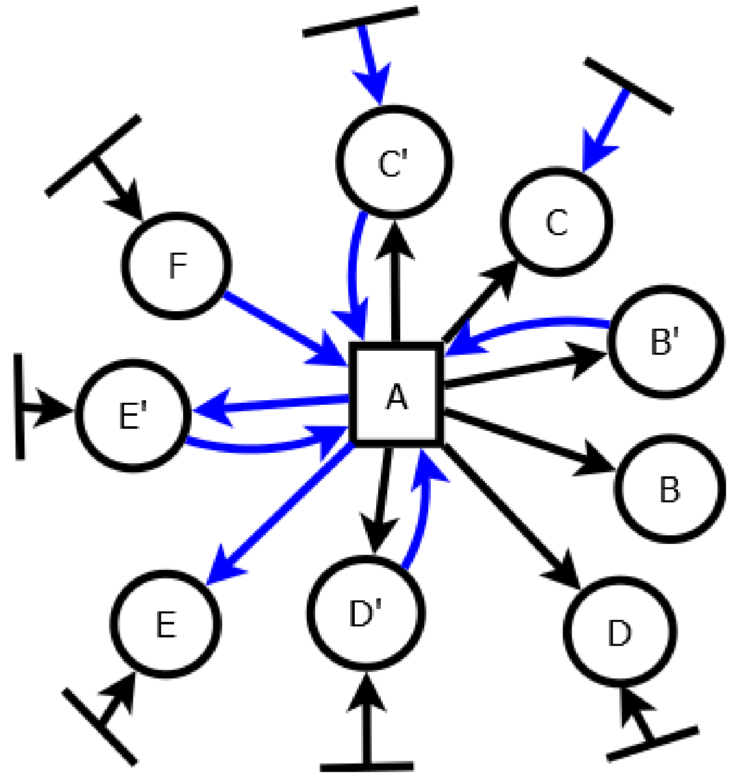
# Weight System

- Weights of source and target nodes determine the type of the edge.
- Strong -> (Weight of Source < Weight of Target).
- Weight of Root = 0.

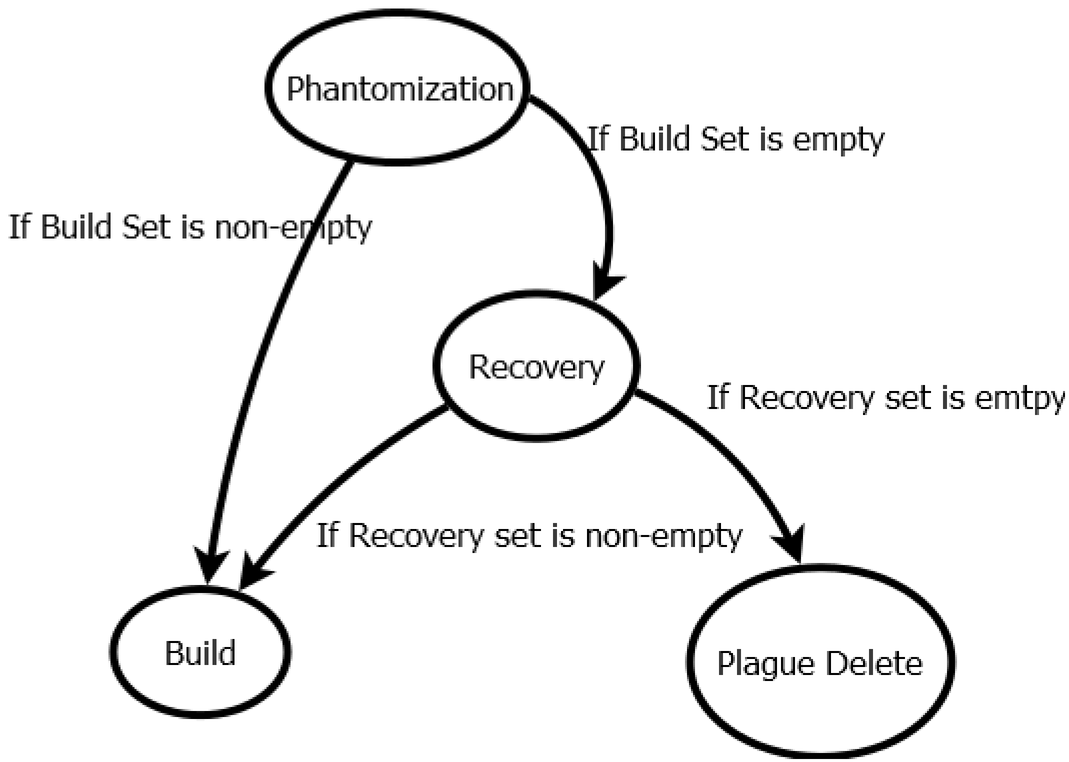


# Node Classification

- A - > Initiator
- B, B’ -> Purely Dependent Set
- C, C’ -> Partially Dependent Set
- D, D’, E, E’, F -> Independent Set
- C’, D’, E’, F -> Supporting Set
- F, D’, E’ -> Build Set
- C’ -> Recovery Set



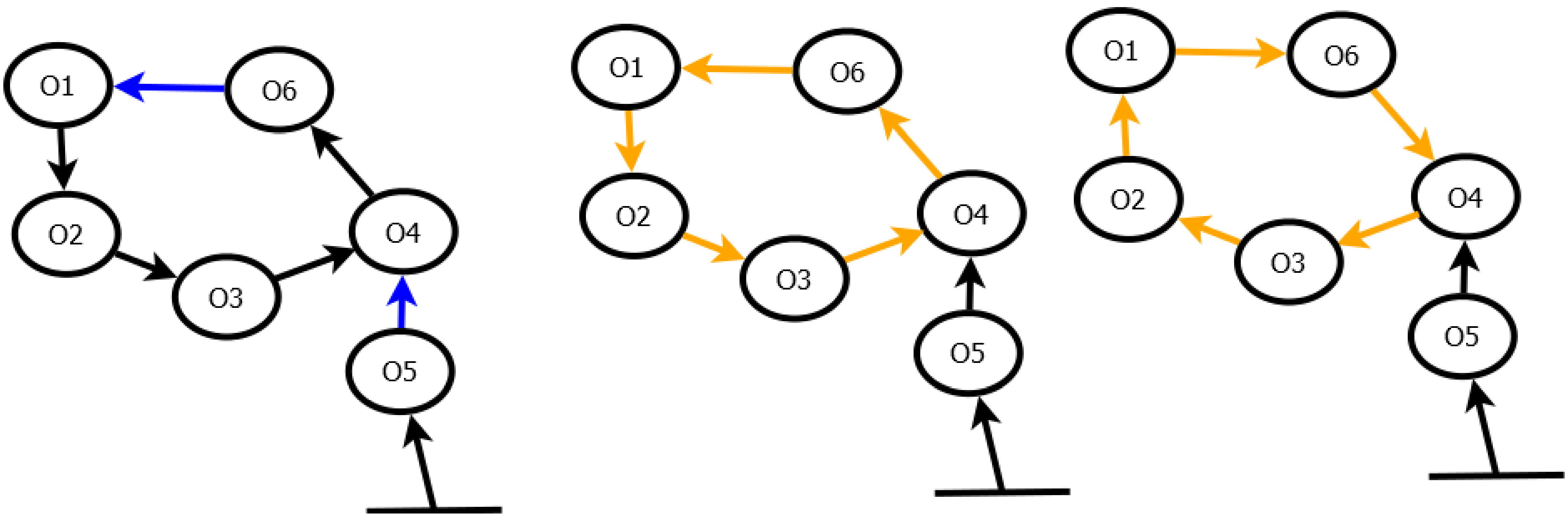
# State Diagram



# Phantomization

- Converts all the internal edges in the non-independent nodes of the subgraph to phantom.
- The process makes sure the internal edges are not counted for the decision process.
- External weak edges are converted into strong during this process.
- The process uses a forward phase and a backward phase to finish operations.

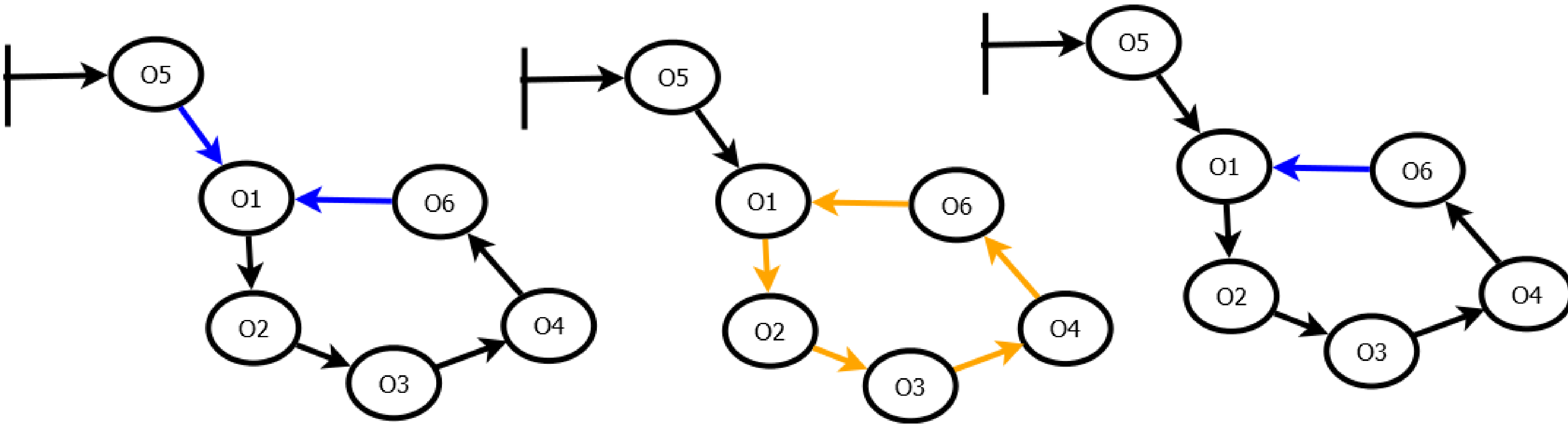
# Phantomization



# Correction

- Recovery, Build, and Plague Delete are correction phases.
- After phantomization, if the initiator has nodes in the build set, it converts all the phantom edges in the subgraph into strong / weak based on weak heuristic.
- Test to find build set: true If the initiator has any strong edges after phatonmization.
- Build by initiator transforms the graph back to regularity.

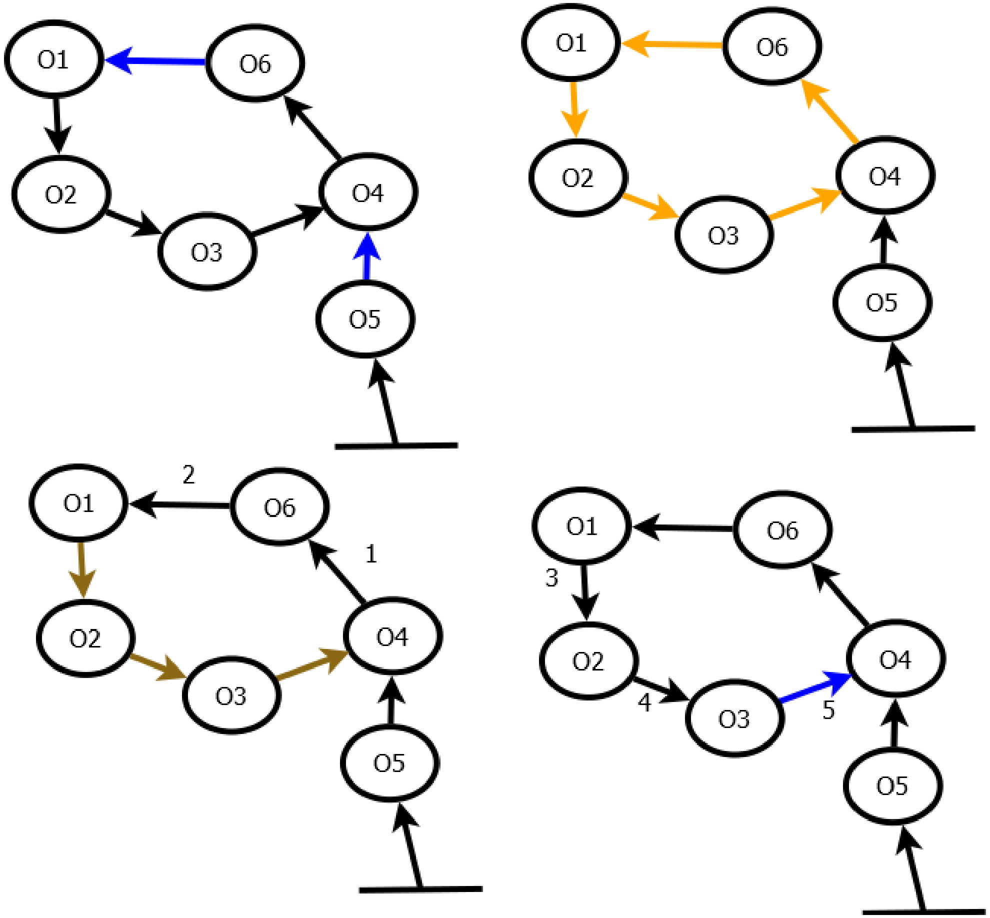
# Build Phase



# Recovery

- Recovery is a complicated phase.
- If initiator does not have any build set, recovery messages are sent.
- A recovery message will only affect the subgraph that is not yet processed.
- On the reverse phase, a recovery node can start building too.

# Recovery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O5
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O1
O6
O2
O3
O4
O5

# Plague Delete

- A node will be deleted only if all the counts are zero.
- A node on receiving plague delete will send plague delete only if there is no strong incoming edge.
- Plague Delete is invoked by the initiator if there is no build set and no recovery set.

# Plague Delete

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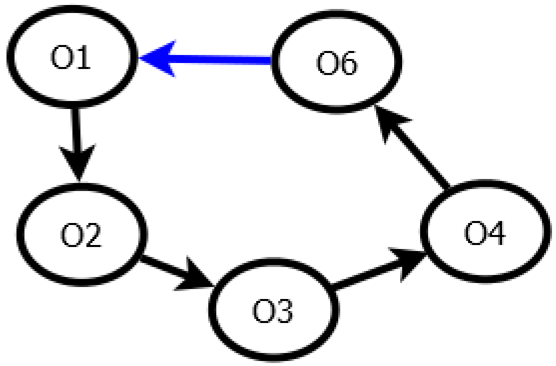
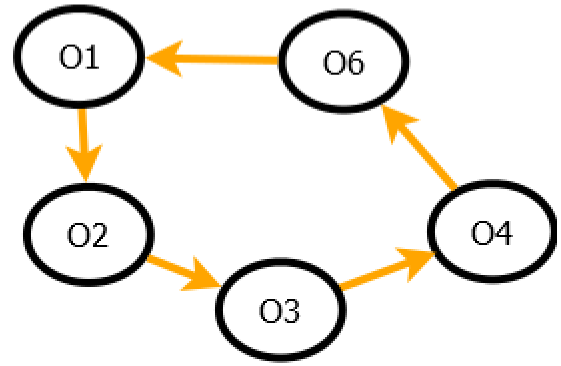
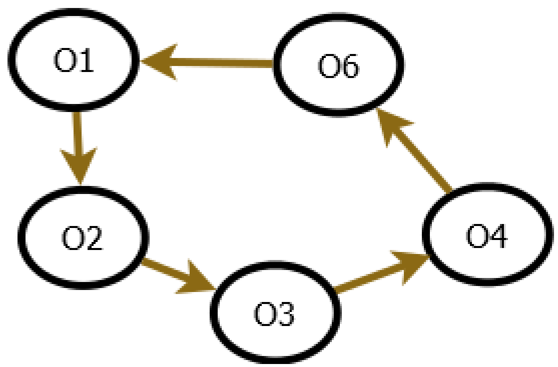
# Plague Delete



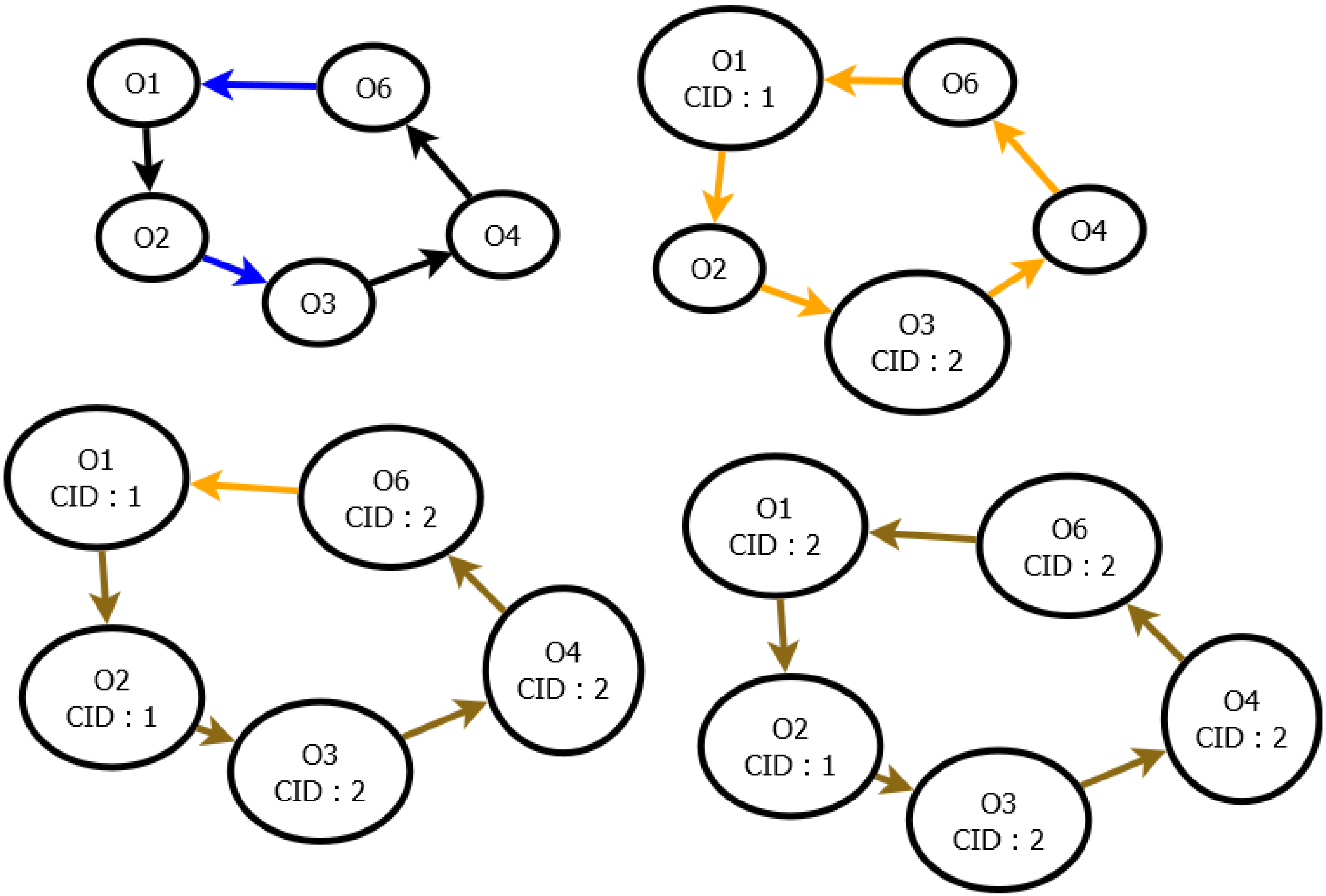
# Isolation property

- The affected subgraph  is not mutated.
- Mutation to the affected subgraph occurs, but do no affect the decisions of the initiator to delete or build.
- Do not affect the decision of recovery set to build by the correction phases.

# Symmetry Breaking

- When multiple collector proces the same subgraph, there is possibility of cycle dependency.
- A leader needs to be elected among conflicting collector operations.
- Each node contains a collector id in the correction phase.
- During the correction phases, nodes are marked with the collector id they belongs to.
- All nodes prefer to be in a collection with higher id.
- All collection ids are unique and so there is a total ordering among collections.

# Acyclic Principle (Isolation)



# Recovery Count

- For the recovery phase to start reverse phase, it must have recovery count equal to phantom count.
- Every recovery message received increments recovery count.
- This creates ordering among subgraphs based on topology, regardless of uncertainty in the collection ids.
- Low collector id cannot increment higher collection recovery count.

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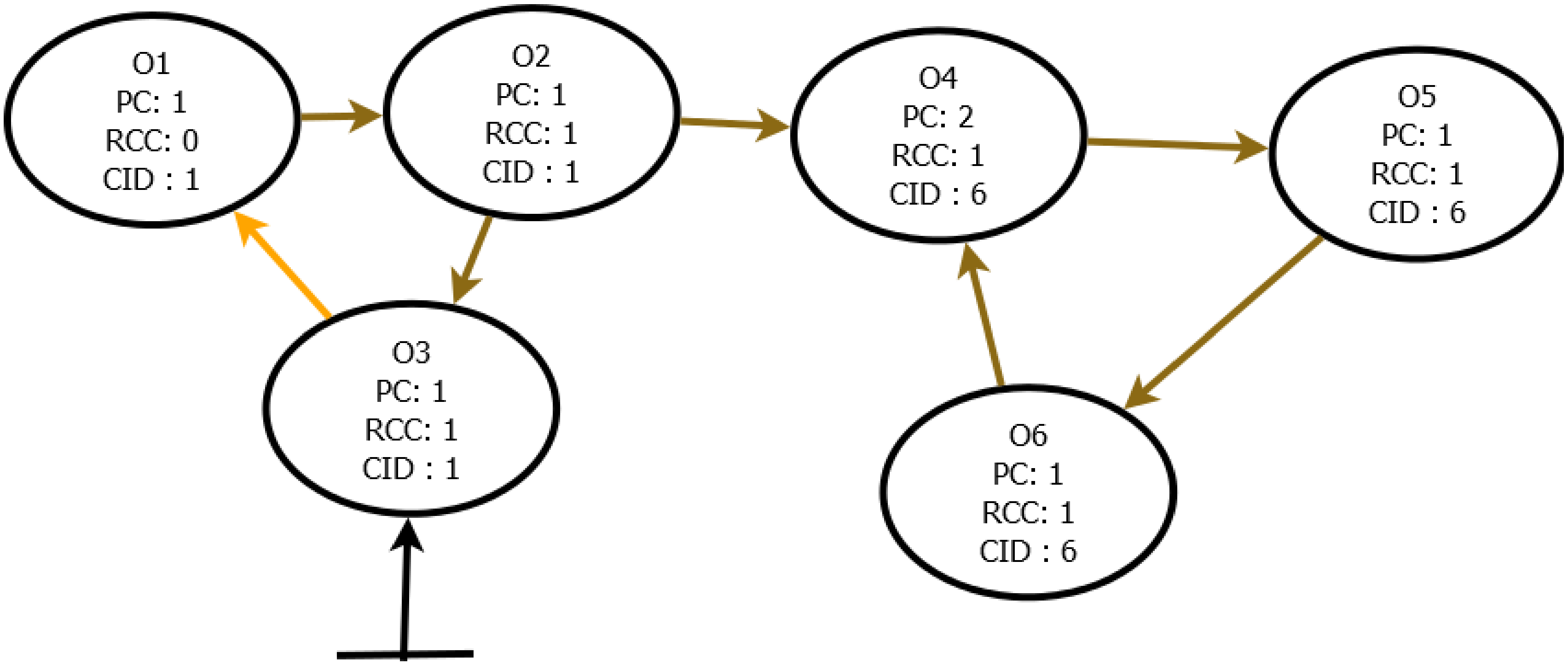
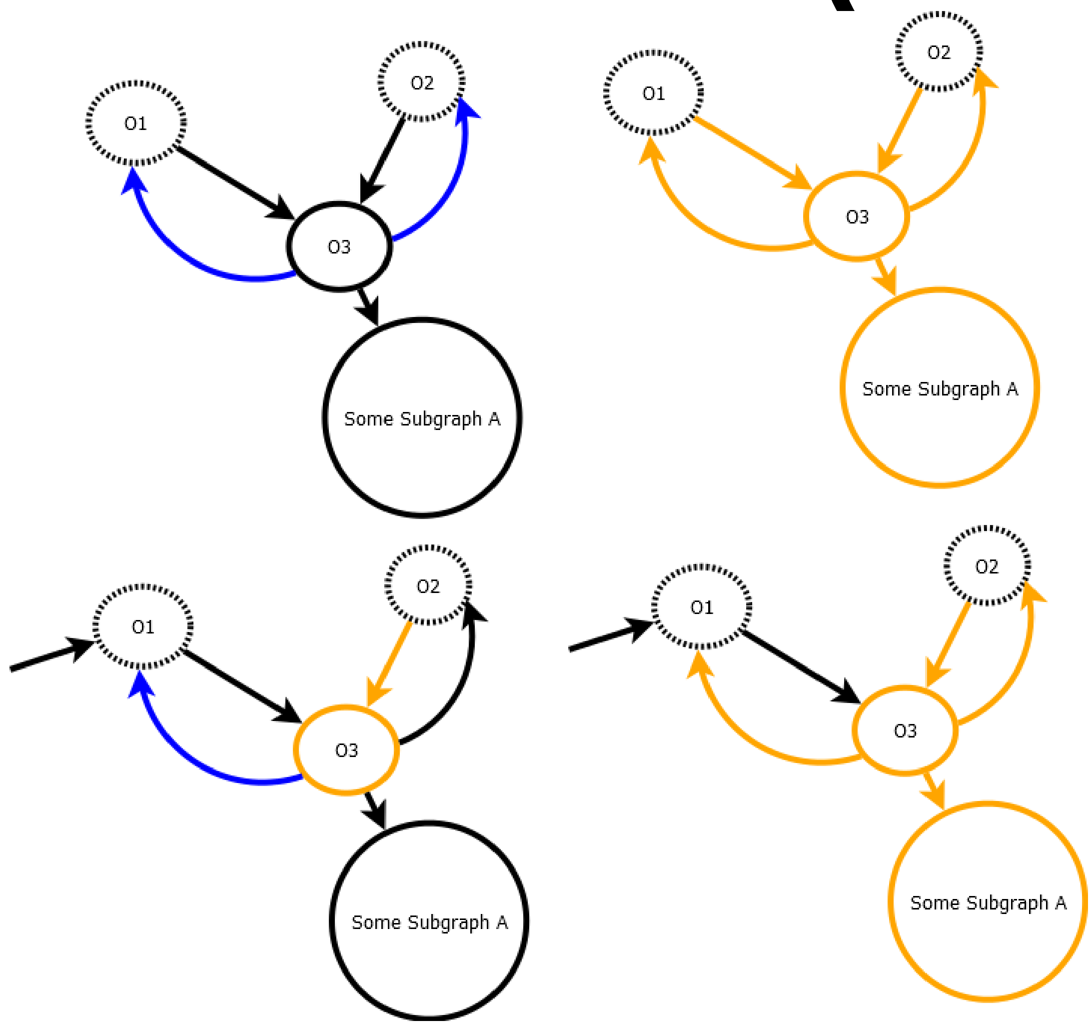
# Topology Ordering (Isolation)



# Transactional Approach

- When two collectors’ operations meet at a point, the lower collection id will not proceed because of symmetry breaking rules.
- To complete the computation of the lower collection process during recovery, recovery phases alone are restarted. Other phases work seamlessly with multiple collectors colliding.
- When multiple collectors of different phases meet, we wait until the reverse phase finishes and then redo if they need to upgrade.

# Redo transaction (Isolation)



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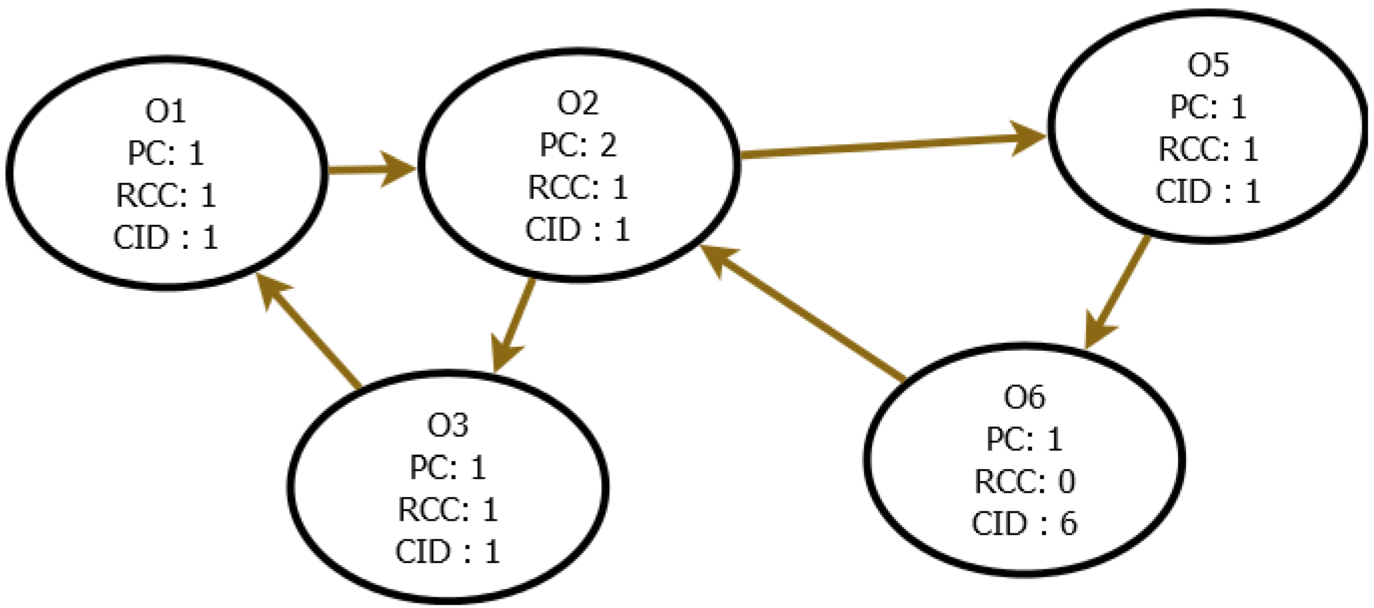
# Recovery Start Over




# Advantages of SWPR

- Concurrent
- Multi-collector algorithm
- Locality-based algorithm
- No global synchronization
- Scalable
- Prompt
- Safe
- Complete
- O(log n) message size.

# Future Work

- Destructor ordering is necessary.
- Fault-tolerance is necessary to make it more reliable.