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(54) **CONCURRENT COLLECTION OF CYCLIC GARBAGE IN REFERENCE COUNTING SYSTEMS**

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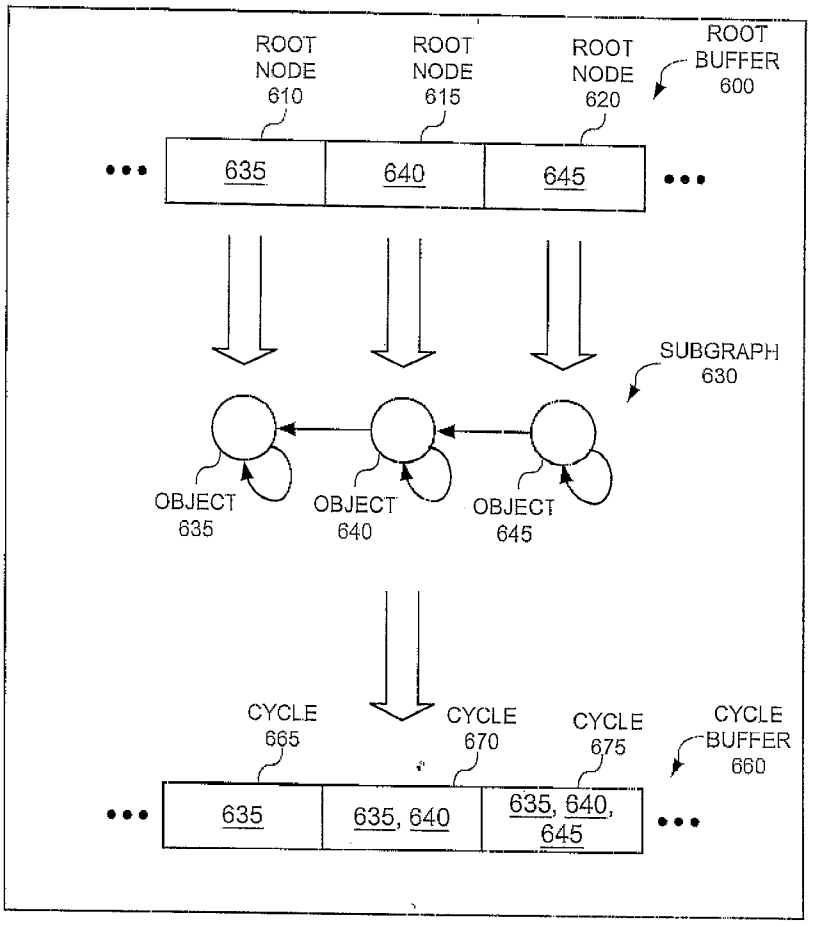
(57) **ABSTRACT**

The present invention provides techniques that allow concurrent collection of cyclic garbage on reference counting systems. In general, candidate objects are found that may be part of cyclic garbage. Each candidate object has a reference count. Two tests are performed to determine if concurrent operations have affected the reference counts of the candidate objects. If concurrent operations have not affected the reference counts, the candidate objects are collected as garbage. Additionally, during garbage collection, the decrements to reference counts are delayed so that increments occur before decrements and so that decrements are held a predetermined time before being applied. This prevents decrementing a reference and collecting a cycle as garbage right before a reference is added to an object in the cycle.



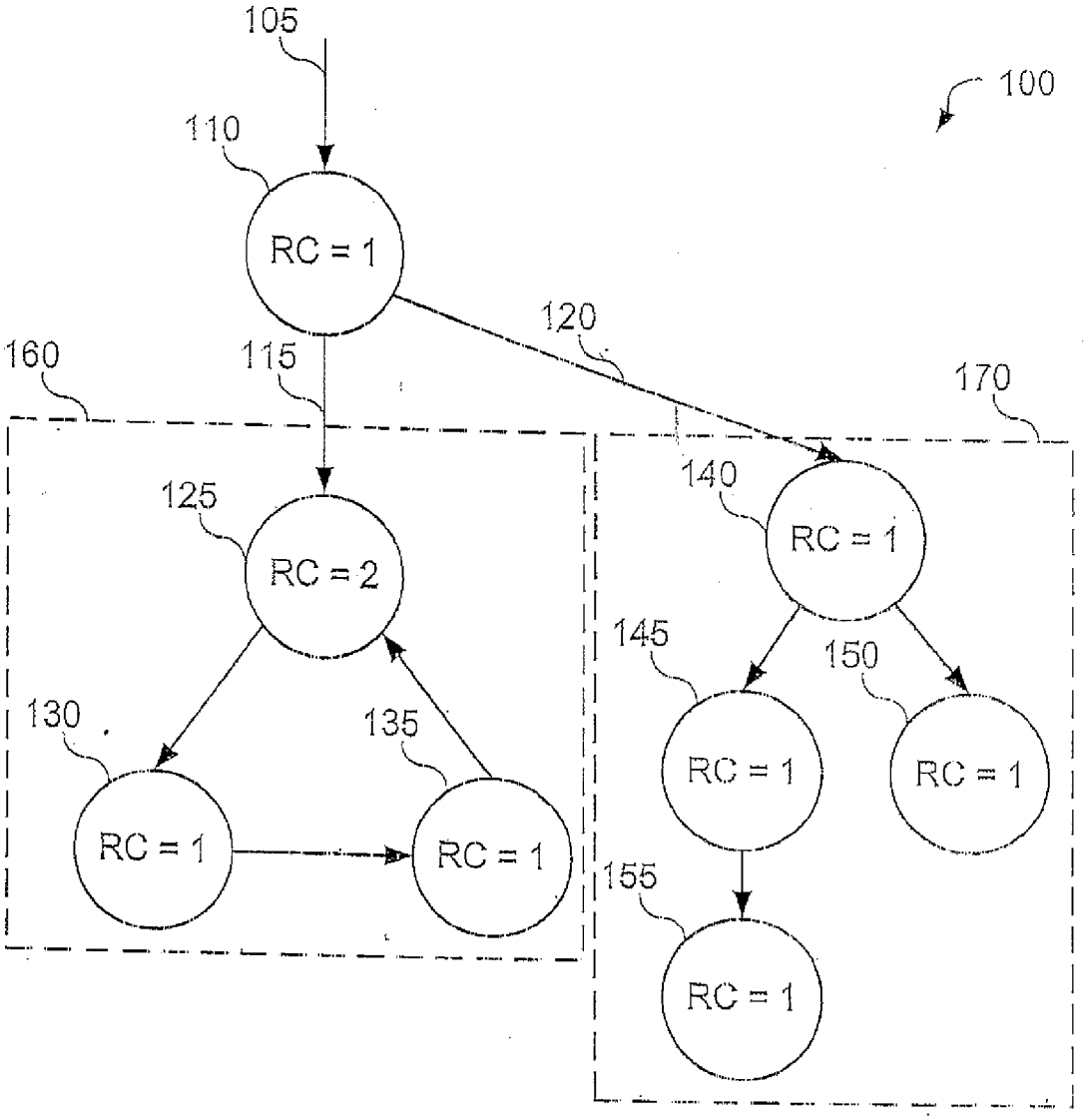


FIG. 1

PRIOR ART

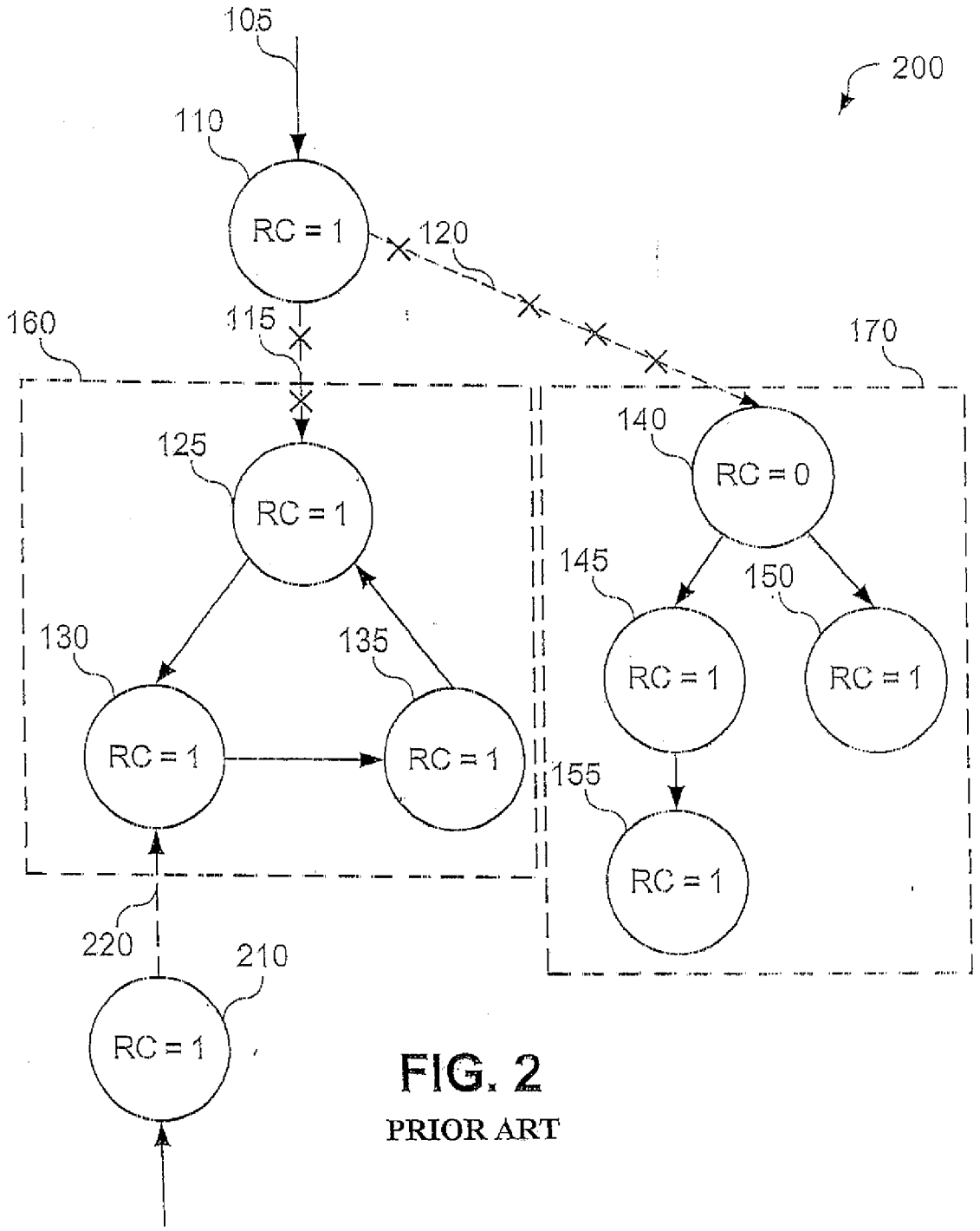


FIG. 2
PRIOR ART

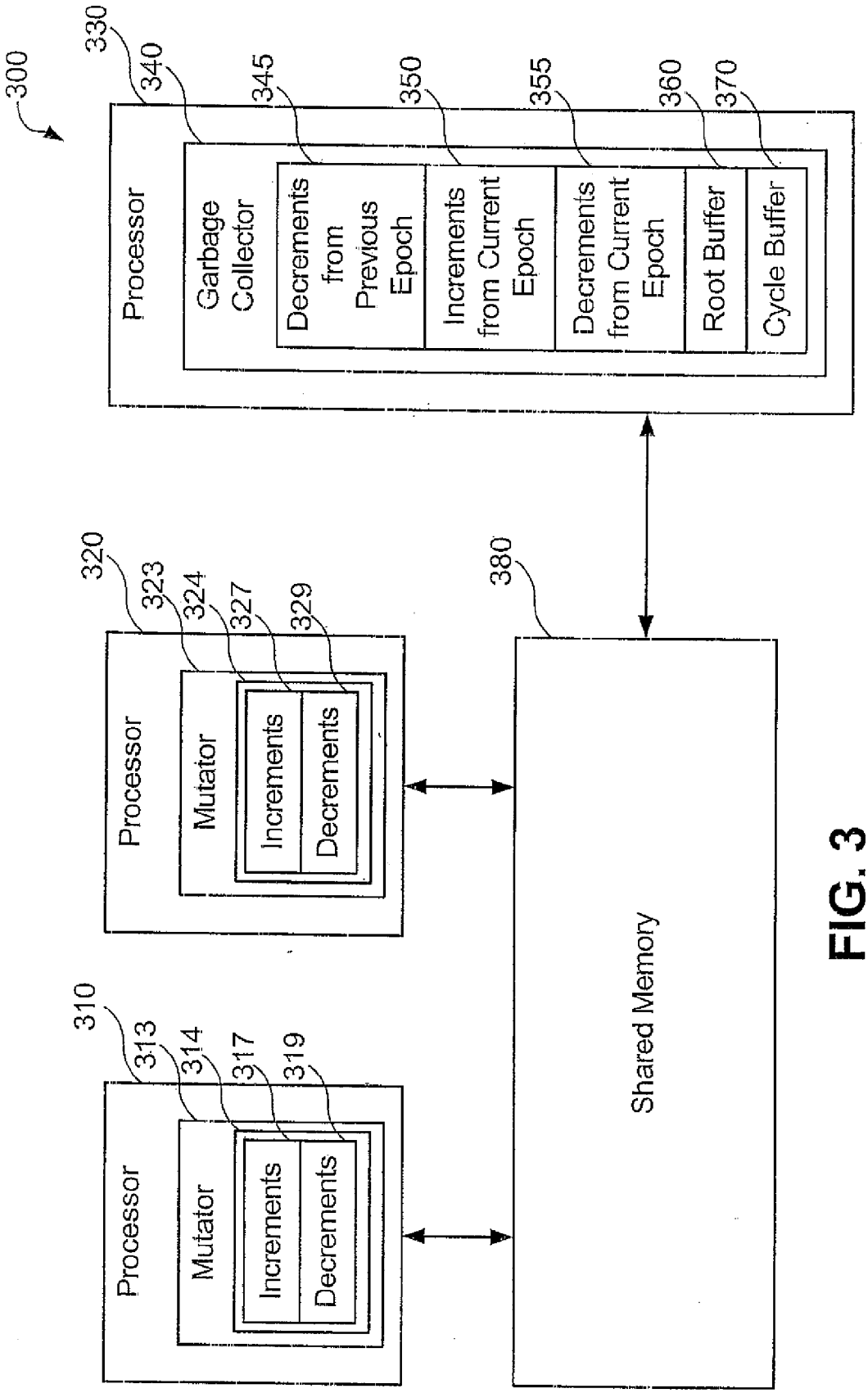

300
330
340
345
350
355
360
370
Processor
Garbage Collector
Decrements from Previous Epoch
Increments from Current Epoch
Decrements from Current Epoch
Root Buffer
Cycle Buffer
320
323
324
327
329
Processor
Mutator
Increments
Decrements
380
310
313
314
317
319
Processor
Mutator
Increments
Decrements
Shared Memory

FIG. 3

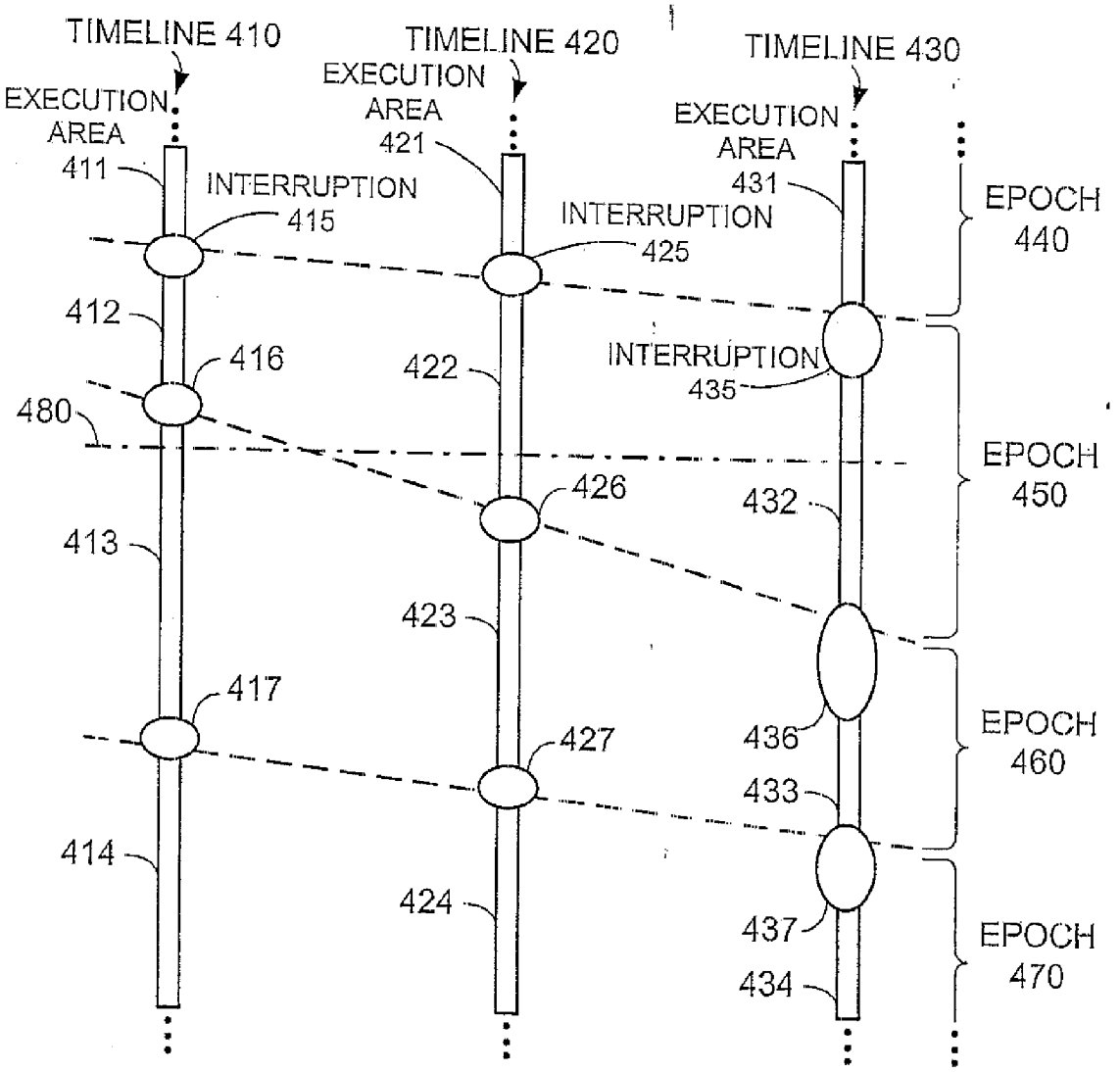

TIMELINE 410
TIMELINE 420
TIMELINE 430
EXECUTION AREA
411
INTERRUPTION
415
421
INTERRUPTION
425
431
EPOCH
440
412
416
422
INTERRUPTION
435
480
EPOCH
450
426
432
413
423
417
427
436
EPOCH
460
433
414
424
437
EPOCH
470
434

FIG. 4

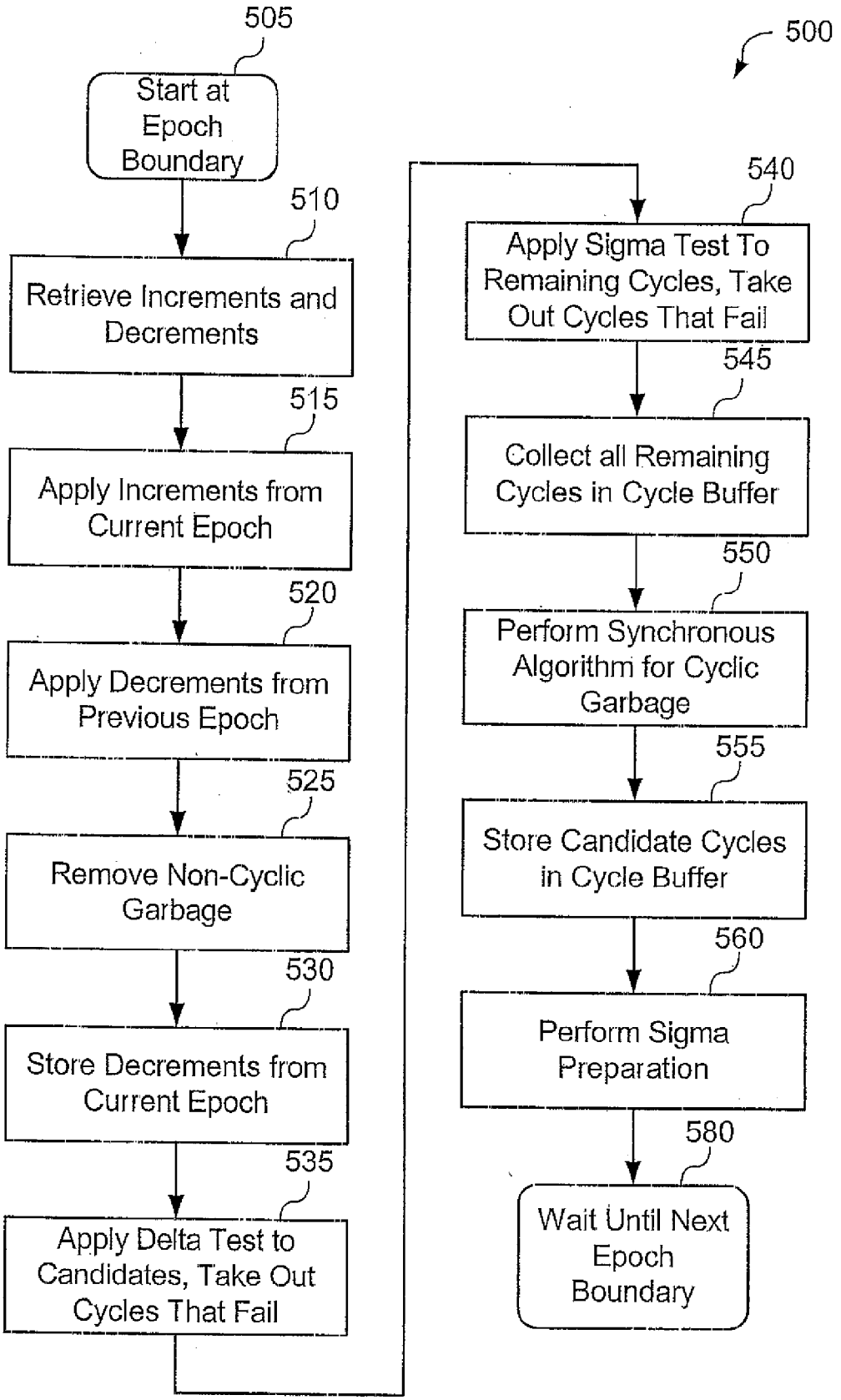

500
505
Start at Epoch Boundary
510
Retrieve Increments and Decrements
515
Apply Increments from Current Epoch
520
Apply Decrements from Previous Epoch
525
Remove Non-Cyclic Garbage
530
Store Decrements from Current Epoch
535
Apply Delta Test to Candidates, Take Out Cycles That Fail
540
Apply Sigma Test To Remaining Cycles, Take Out Cycles That Fail
545
Collect all Remaining Cycles in Cycle Buffer
550
Perform Synchronous Algorithm for Cyclic Garbage
555
Store Candidate Cycles in Cycle Buffer
560
Perform Sigma Preparation
580
Wait Until Next Epoch Boundary

FIG. 5

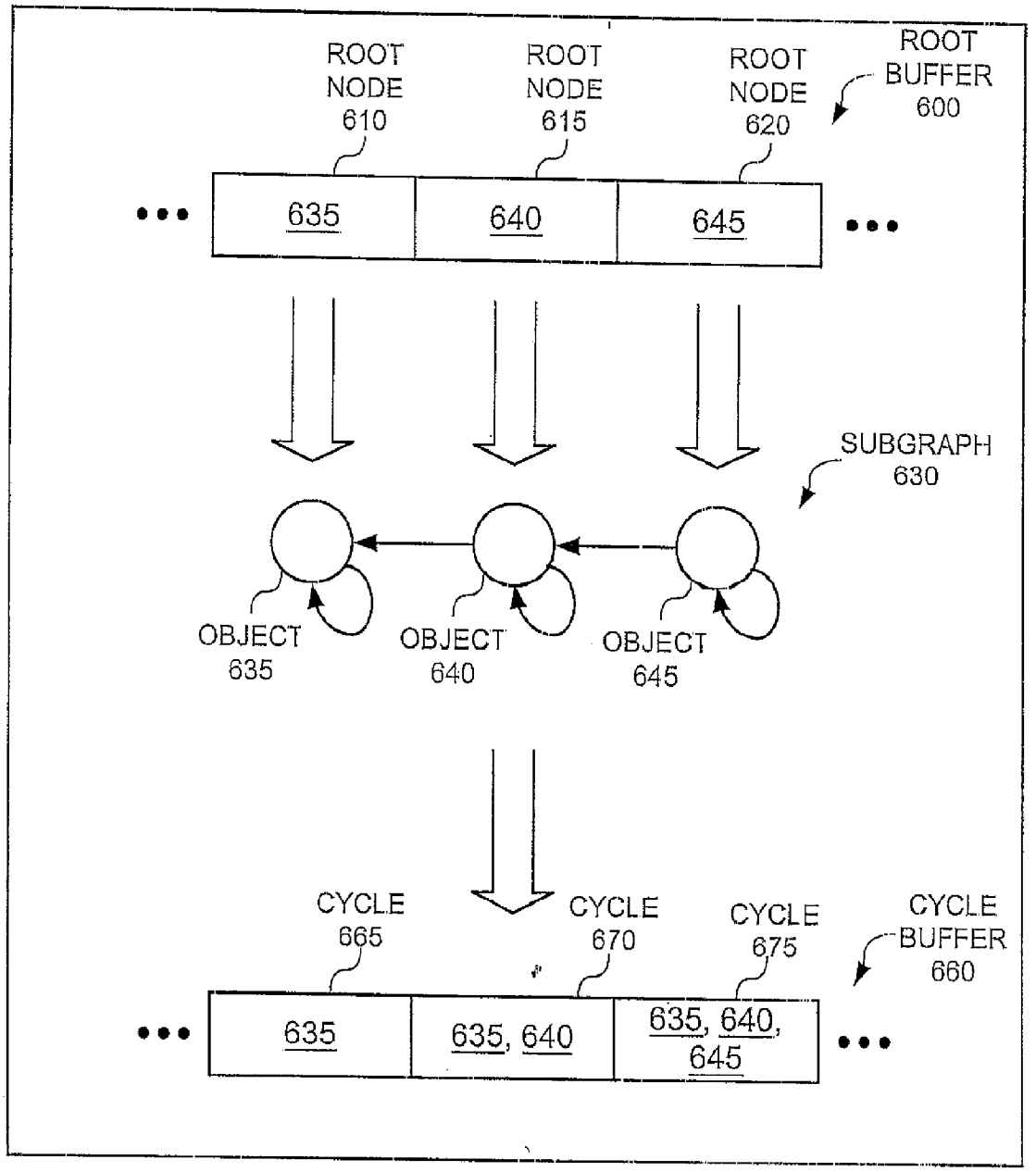

ROOT NODE 610
ROOT NODE 615
ROOT NODE 620
ROOT BUFFER 600
635
640
645
SUBGRAPH 630
OBJECT 635
OBJECT 640
OBJECT 645
CYCLE 665
CYCLE 670
CYCLE 675
CYCLE BUFFER 660
635
635, 640
635, 640, 645

FIG. 6

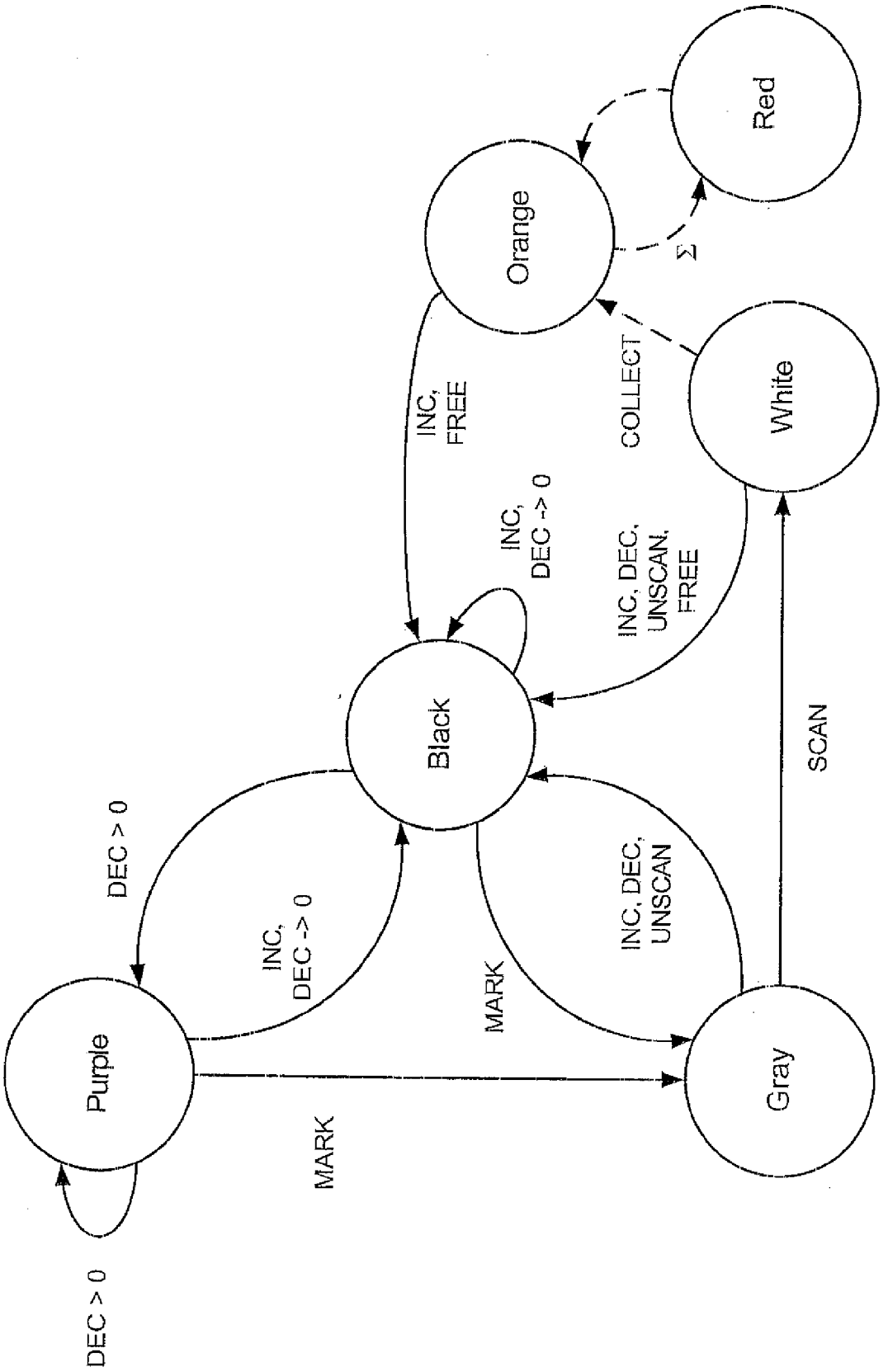

Red
Orange
Σ
INC, FREE
COLLECT
White
INC, DEC-> 0
INC, DEC, UNSCAN, FREE
Black
DEC > 0
INC, DEC-> 0
MARK
INC, DEC, UNSCAN
SCAN
Purple
Gray
MARK
DEC > 0

FIG. 7

```
Increment(S)
  RC(S) = RC(S) + 1
  ScanBlack(S)

Decrement(S)
  RC(S) = RC(S) - 1
  if (RC(S) == 0)
    Release(S)
  else
    PossibleRoot(S)

Release(S)
  for I in children(S)
    Decrement(I)
  color(S) = black
  if (! buffered(S))
    Free(S)

PossibleRoot(S)
  ScanBlack(S)
  color(S) = purple
  if (! buffered(S))
    buffered(S) = true
    append S to Roots

ProcessCycles()
  FreeCycles()
  CollectCycles()
  SigmaPreparation()

CollectCycles()
  MarkRoots()
  ScanRoots()
  CollectRoots()

MarkRoots()
  for S in Roots
    if (color(S) == purple
        and RC(S) > 0)
      MarkGray(S)
    else
      remove S from Roots
      buffered(S) = false
      if (RC(S) == 0)
        Free(S)

ScanRoots()
  for S in Roots
    Scan(S)

CollectRoots()
  for S in Roots
    if (color(S) == white)
      CurrentCycle = empty
      CollectWhite(S)
      append CurrentCycle
        to CycleBuffer
    else
      buffered(S) = false
    remove S from Roots

MarkGray(S)
  if (color(S) != gray)
    color(S) = gray
    CRC(S) = RC(S)
    for I in children(S)
      MarkGray(I)
  else if (CRC(S) > 0)
    CRC(S) = CRC(S) - 1

Scan(S)
  if (color(S) == gray
      and CRC(S) == 0)
    color(S) = white
    for I in children(S)
      Scan(I)
  else
    ScanBlack(S)

ScanBlack(S)
  if (color(S) != black)
    color(S) = black
    for I in children(S)
      ScanBlack(I)

CollectWhite(S)
  if (color(S) == white)
    color(S) = orange
    buffered(S) = true
    append S to CurrentCycle
    for I in children(S)
      CollectWhite(I)
```

FIG. 8

```
SigmaPreparation()
  for C in CycleBuffer
    for N in C
      color(N) = red
      CRC(N) = RC(N)
    for N in C
      for M in children(N)
        if (color(M) == red
            and CRC(M) > 0)
          CRC(M) = CRC(M)-1
    for N in C
      color(N) = orange

FreeCycles()
  last = |CycleBuffer|-1
  for i = last to 0 by -1
    C = CycleBuffer[i]
    if (DeltaIest(C)
        and SigmaIest(C))
      FreeCycle(C)
    else
      Refurbish(C)
  clear CycleBuffer

DeltaIest(C)
  for N in C
    if (color(N) != orange)
      return false
  return true

SigmaIest(C)
  externRC = 0
  for N in C
    externRC = externRC+CRC(N)
  return (externRC == 0)

Refurbish(C)
  first = true
  for N in C
    if ((first and
         color(N)==orange) or
         color(N)==purple)
      color(N) = purple
      append N to Roots
    else
      color(N) = black
      buffered(N) = false
    first = false

FreeCycle(C)
  for N in C
    color(N) = red
  for N in C
    for M in children(N)
      CyclicDecrement(M)
  for N in C
    Free(N)

CyclicDecrement(M)
  if (color(M) != red)
    if (color(M) == orange)
      RC(M) = RC(M) - 1
      CRC(M) = CRC(M) - 1
    else
      Decrement(M)
```

FIG. 9

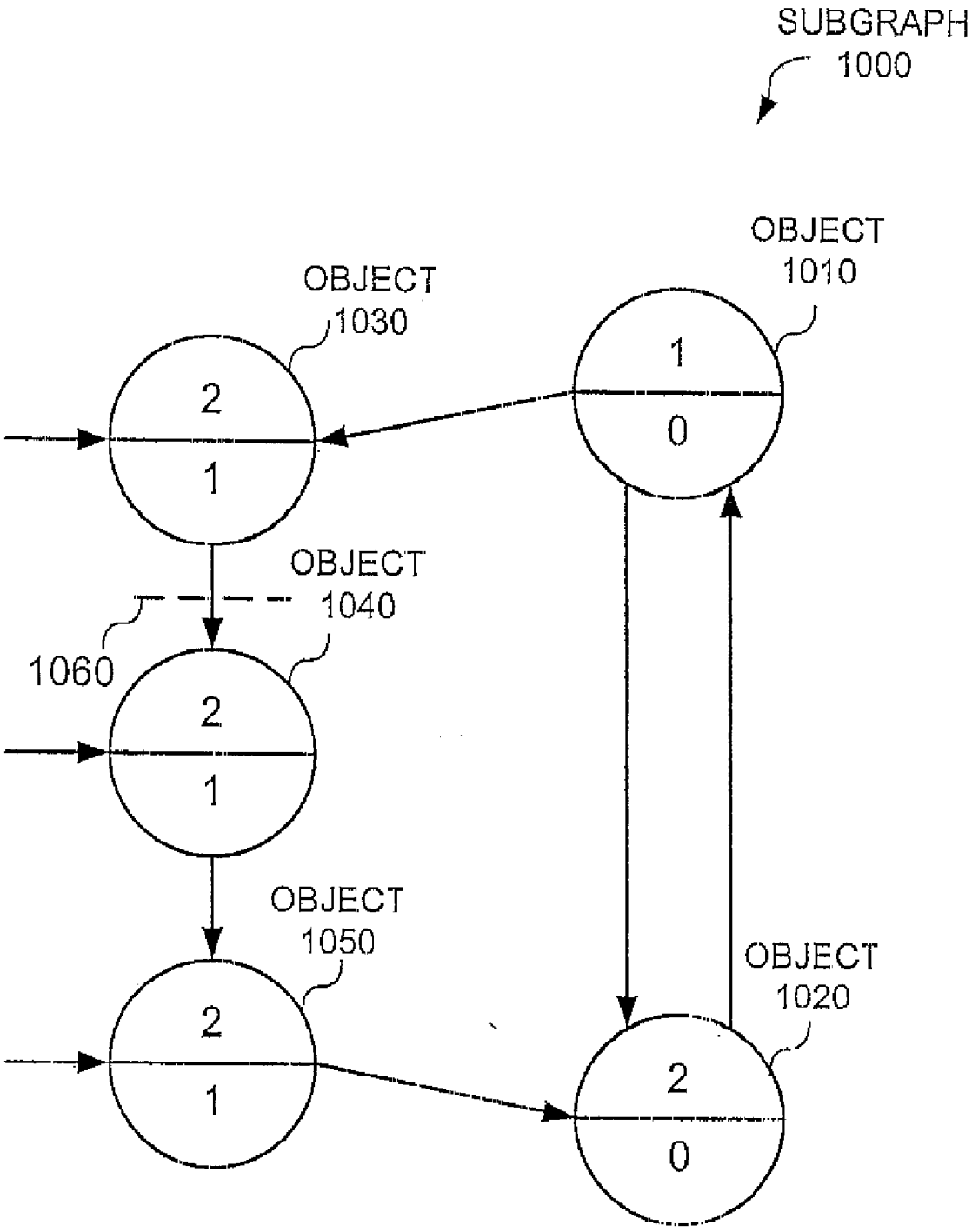

SUBGRAPH
1000
OBJECT
1010
OBJECT
1030
OBJECT
1040
1060
OBJECT
1050
OBJECT
1020
2
1
1
0
2
1
2
1
2
0

FIG. 10

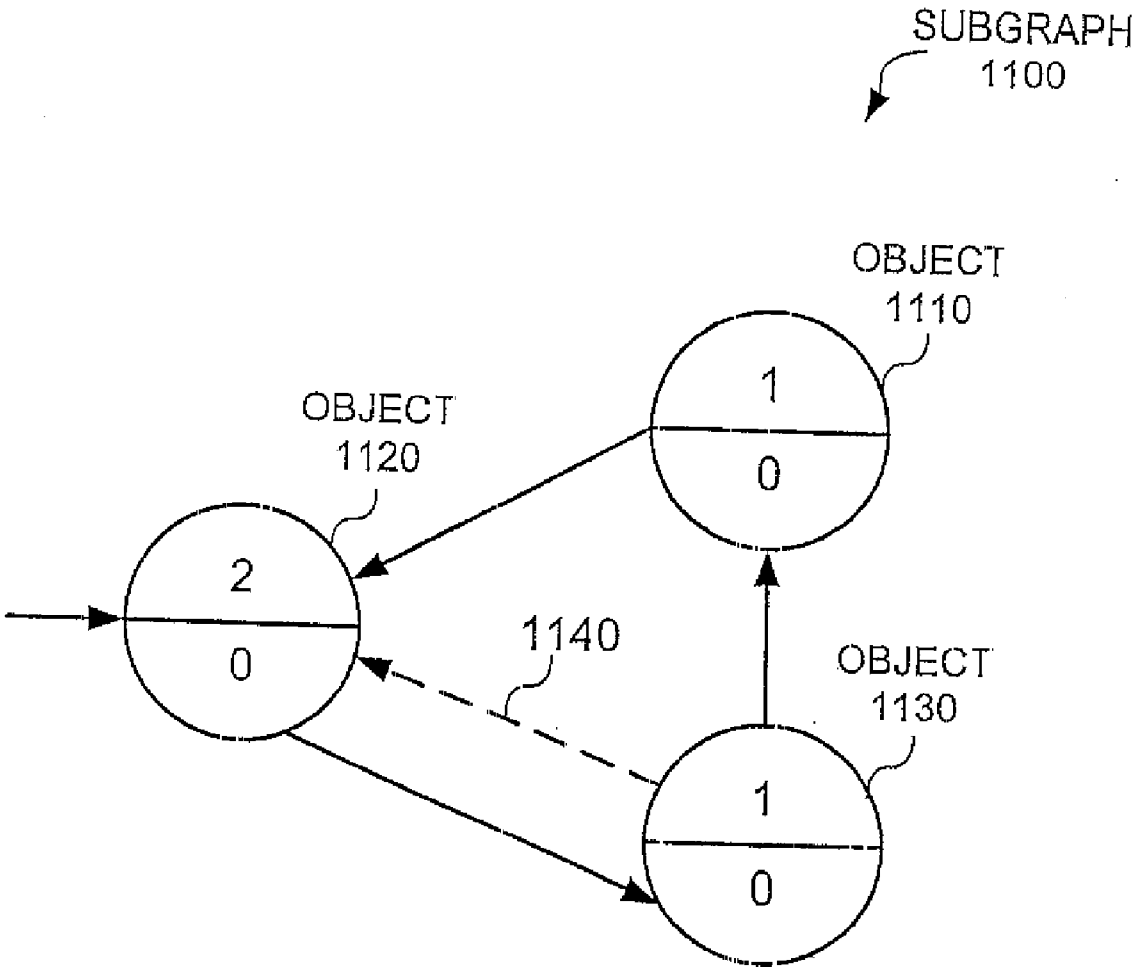

SUBGRAPH
1100
OBJECT
1110
1
0
OBJECT
1120
2
0
1140
OBJECT
1130
1
0

FIG. 11

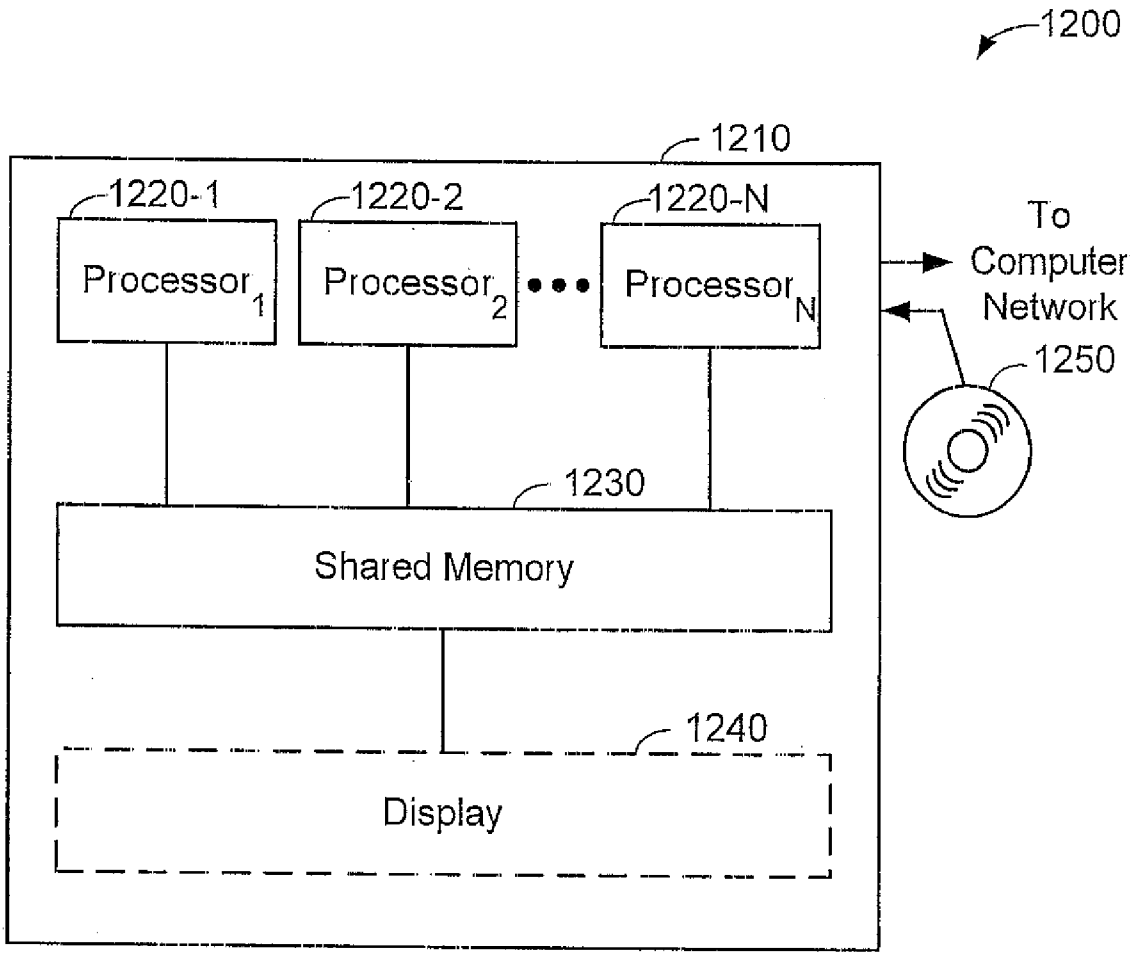

1200
1210
1220-1
1220-2
1220-N
Processor 1
Processor 2
Processor N
To Computer Network
1250
1230
Shared Memory
1240
Display

FIG. 12

CONCURRENT COLLECTION OF CYCLIC GARBAGE IN REFERENCE COUNTING SYSTEMS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 60/254,615, filed Dec. 11, 2000, and U.S. Provisional Patent Application No. 60/254,691, filed Dec. 11, 2000 and U.S. patent application Ser. No. 10/013,148, filed Dec. 10, 2001.

FIELD OF THE INVENTION

[0002] The present invention relates to garbage collection in computer systems and, more particularly, relates to concurrent collection of cyclic garbage in reference counting systems.

BACKGROUND OF THE INVENTION

[0003] The term "garbage" is used to describe an object or data element that is no longer accessible by a computer program. Some systems are designed with no garbage detection and collection programs. In these systems, it is up to the programmer to remember to reclaim objects and data that is no longer accessible. Garbage occupies part of the memory of a computer system but serves no purpose. If a computer program does not run for very long or is infrequently run, garbage collection is not a problem because the computer system generally has plenty of memory. However, if the program creates garbage and is run for a long time or frequently, the extraneous garbage can grow to occupy all of the useful memory of the computer system. This will cause a system shutdown or other deleterious effects. Today, programs are designed to run continuously all day, every day. Business servers simply cannot experience unscheduled shutdowns.

[0004] The effect of garbage has been known from the beginning of the computer era. In fact, forty years ago, two methods of automatic garbage collection for computer systems were introduced: reference counting and tracing. Reference counting is described in Collins, "A Method for Overlapping and Erasure of Lists," Communications of the Ass'n of Computing Machinery (ACM) 3, 655-657 (1960), while tracing is described in McCarthy, "Recursive Functions of Symbolic Expressions and Their Computation by Machine," Communications of ACM 3, 184-195 (1960), the disclosures of which are incorporated herein by reference. Briefly, in reference counting, a reference count is used in an object to track how many other objects reference this object. Reference counts are incremented and decremented, and a reference count of zero indicates that the object is garbage because it is unreachable by any other object. In tracing, the entire object graph is traced until garbage is found. Since this early time, tracing collectors and their variants have been much more widely used due to perceived deficiencies in reference counting.

[0005] Changes in the relative costs of memory and processing power, and the widespread adoption of languages that employ garbage collection, have modified the landscape. As processor clock speeds increase while Random Access Memory (RAM) becomes plentiful but not significantly faster, certain properties of reference counting make it more appealing. Moreover, the purported extra processing power required is likely to be less relevant.

[0006] At the same time, the incorporation of garbage collection by the programming language Java has thrust the problem into the mainstream. Now, large, mission-critical systems are being built in Java. This stresses the flexibility and scalability of the underlying garbage collection implementations used in Java. As a result, the supposed advantages of tracing collectors, namely simplicity and low overhead, are being eroded as they are being made ever more complex in an attempt to address the real-world requirements of large and varied programs.

[0007] Furthermore, the fundamental assumption behind tracing collectors, namely that it is acceptable to periodically trace all of the live objects in the heap (an area of memory reserved for data that is created during runtime), will not necessarily scale to the very large main memories that are becoming increasingly common.

[0008] There are three primary problems with reference counting: (1) the storage overhead associated with keeping a count for each object; (2) the runtime overhead of incrementing and decrementing the reference count each time a pointer is copied; and (3) the inability to detect cyclic garbage and consequent necessity of including a second garbage collection technique to deal with cyclic garbage.

[0009] The inability to collect cyclic garbage (also called "cycles" herein) is generally considered to be the greatest weakness of reference counting collectors. It places the burden on the programmer to break cycles explicitly, requires special programming idioms, or requires a tracing collector to collect the cycles.

[0010] The problem of cycles in reference counting systems is illustrated in FIGS. **1** and **2**. FIG. **1** shows a subgraph **100** containing a number of nodes **110**, **125**, **130**, **135**, **140**, **145**, **150**, and **155** therein. When a computer program runs, it creates a number of objects or data structures or both. The interrelationship between the program, the objects, and the data structures is commonly called a graph. FIG. **1** shows a subset of a graph created by an executing program (the program is not shown). This subset is subgraph **100**.

[0011] Subgraph **100**, as discussed above, contains a number of nodes **110**, **125**, **130**, **135**, **140**, **145**, **150**, and **155**. Each node represents an object ox part of a data structure. Between each node is one or more edges. For instance, between node **110** and node **125** is edge **115**, and between node **110** and node **140** is edge **120**. Additionally, node **110** is connected to the rest of the graph (not shown) through edge **105**. Each edge represents a reference from one node to another node. In FIG. **1**, node **110** is referencing node **125** through edge **115**, and it is also referencing node **140** through edge **120**.

[0012] In a reference counting system, the reference count for each node is tracked. For instance, node **125** has a Reference Count (RC) of two because nodes **110** and **135** reference node **125**. In FIG. **1**, subgraph **160** represents a cyclic structure, while subgraph **170** represents an acyclic structure. Subgraph **160** represents a cyclic structure because there is a series of edges that traverses nodes and that starts at node **125** and ends at **125**. In other words, one can traverse this graph by starting at one node and ending at the same node. Thus, subgraph **160** is cyclic. In subgraph

170, conversely, there is no series of edges that traverses nodes and that starts at one node and ends at the same node. Thus, subgraph **170** is acyclic.

[**0013**] FIG. **2** shows a resultant subgraph **200** that occurs after the program removes the references from node **110** that created edges **115** and **120**. Even though the program explicitly removes the references, a "mutator" actually performs the low level removal of references. The process undertaken by the mutator is generally hidden from a programmer. A garbage collector will easily recognize that subgraph **170** is garbage, because the reference count for node **140** is zero. A zero indicates that node **140** is no longer being referenced by the program, and, therefore, the node may be removed. Because node **140** can be removed, nodes **145**, **150**, and **155** can also be removed.

[**0014**] Subgraph **160** is more challenging for a garbage collector. There is no node that contains a reference count of zero. Even though this subgraph **160** cannot be accessed by the program, the reference counts are non-zero. A garbage collector in this instance will have to select a node and search through the entire subgraph to determine that no node in the subgraph is referenced by a node outside of the subgraph. It can then eliminate subgraph **160** as garbage.

[**0015**] Many reference counting systems use a "stop the world" type of synchronous garbage collection, where all processes or threads other than the garbage collector are stopped. This means that the reference counts are not changing while the garbage collector collects garbage. However, "stop the world" garbage collection can take too much time. In fact garbage collectors of this type have been known to run for many seconds or even minutes on large systems, which is too long for critical applications. Thus, concurrent garbage collection, which allows processes to run during garbage collection, is becoming increasingly necessary.

[**0016**] Concurrent collection of garbage creates additional problems, however. One of these problems is illustrated in FIG. **2**. In FIG. **2**, subgraph **160** is considered to be garbage once edge **115** is removed. However, node **210** might add edge **220** shortly before edge **115** is removed. This would cause the reference count for node **130** to be increased to two. If garbage collection occurs before edge **220** is added but after edge **115** is removed, a garbage collector will determine that subgraph **160** and its nodes **125**, **130**, and **135** are garbage. However, they are not garbage because node **210** has added or will add edge **220** to allow node **210** to reference node **130**.

[**0017**] Concurrent collection of garbage therefore adds additional problems to garbage collection in reference counting garbage collection systems. Techniques for concurrent collection of garbage exists, but these techniques do not use reference counting.

[**0018**] Thus, better techniques are needed for concurrent collection of cyclic garbage in reference counting computer systems.

SUMMARY OF THE INVENTION

[**0019**] The present invention provides techniques that allow concurrent collection of cyclic garbage on reference counting systems. In general, candidate objects are found that may be part of cyclic garbage. Each candidate object has a reference count. Two tests are performed to determine if concurrent operations have affected the reference counts of the candidate objects. If concurrent operations have not affected the reference counts, the candidate objects are collected as garbage. Additionally, during garbage collection, the decrements to reference counts are delayed so that increments occur before decrements and so that decrements are held a predetermined time before being applied. This prevents decrementing a reference and collecting a cycle as garbage right before a reference is added to an object in the cycle

[**0020**] A more complete understanding of the present invention, as well as further features and advantages of the present invention, will be obtained by reference to the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[**0021**] FIGS. **1** and **2** are exemplary diagrams of a subgraph and data structures therein;

[**0022**] FIG. **3** is a block diagram of a system that performs concurrent reference counting garbage collection in accordance with one embodiment of the present invention;

[**0023**] FIG. **4** is a diagram of execution timelines for three processors, one of which executes a garbage collector, in accordance with one embodiment of the present invention;

[**0024**] FIG. **5** is a flowchart of a method of concurrent garbage collection for cyclic data structures in a reference counting computer system, in accordance with one embodiment of the present invention;

[**0025**] FIG. **6** is a block diagram of the creation of a cycle buffer from a root directory for one particular subgraph, in accordance with one embodiment of the present invention;

[**0026**] FIG. **7** is a state transition graph for concurrent garbage collection of cyclic data structures in a reference counting computer system, in accordance with one embodiment of the present invention;

[**0027**] FIGS. **8** and **9** are exemplary listings of pseudocode instructions used to implement concurrent garbage collection of cyclic data structures in a reference counting computer system, in accordance with one embodiment of the present invention;

[**0028**] FIGS. **10** and **11** are diagrams of cyclic data structures and possible concurrent operations that can possibly create inaccuracies if both tests of the present invention are not performed; and

[**0029**] FIG. **12** is a block diagram of an exemplary system suitable fox carrying out embodiments of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[**0030**] The present invention provides techniques that allow concurrent collection of cyclic garbage on reference counting systems. In general, candidate objects are found that may be part of cyclic garbage. To find candidate objects that may be part of cyclic garbage, techniques in the following reference may be used: D. Bacon, "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," attorney docket number YOR920000850US2, filed on Dec. 7, 2001, the disclosure of which is hereby incor-

porated by reference. However, the tests of the present invention do not depend on any property of the technique that finds candidate objects. Thus, any technique that can find candidate objects may be used.

[0031] Generally, a toot buffer is used to store objects that may be roots of cyclic garbage. From the root buffer, a cycle buffer is created. Basically, each root in the root buffer describes a cycle that may be garbage. These cycles are added to the cycle buffer. Thus, the cycle buffer contains a number of complete cycles, where each cycle may be garbage. The cycle buffet increases the speed at which cycles are traversed. The root buffer and cycle buffer are not necessary to the practice of the present invention, and other types of data structures may be used.

[0032] Two tests are performed on the cycles in the cycle buffer to determine if concurrent operations have affected the reference counts of the candidate objects. These two tests are called the "delta test," or Δ-test, and "sigma test," or Σ-test, herein. If concurrent operations have not affected the reference counts, the candidate objects from the cycles in the cycle buffer are collected as garbage.

[0033] Additionally, during garbage collection, the decrements to reference counts are delayed so that increments occur before decrements. Moreover, decrements are further delayed a predetermined period. Generally, increments from a current epoch are applied to reference counts, as are decrements from a previous epoch. The definition of "epoch" changes depending on the process being discussed. For single processors, each "epoch" is separated by collections, which is where increments and decrements are sent to a garbage collector. For a number of processors in a system where a garbage collector runs on one of the processors, on the processor running the garbage collector, each epoch is separated by a period when the garbage collector has acted on the increments and decrements. Each epoch ends when all processors have again sent the contents of their mutator buffers to the garbage collector. Decrements from the current epoch are stored and applied in the next epoch. This prevents decrementing a reference and collecting a cycle as garbage right before a reference is added to an object in the cycle.

[0034] Before proceeding further, it is worthwhile to discuss some conventions used in this specification. The terms "node" and "object" are considered interchangeable, as are "edge" and "reference," and "graph" and "object diagram." An edge connects one node to the same node or another node in a graph, while a reference connects one object to itself or another object in an object diagram. Graph theorists tend to use the former terms, while software engineers use the latter terms. Additionally, the term "cycle" will be used to indicate a series of nodes that are cyclic and potentially garbage.

[0035] Also, nodes or objects will generally be "marked" with a "color" in the upcoming discussion. The color analogy is widely used in literature that discusses garbage collection, so it will be retained here. The meanings of the colors used herein are as follows: black indicates that a node is "in use" or "free"; gray indicates that a node is a possible member of a cycle; white indicates that a node is a member of a cycle; purple indicates a possible root of a cycle; red indicates that a node is part of a candidate cycle undergoing sigma computation; and orange indicates that a node is part of a candidate cycle awaiting an epoch boundary.

[0036] Referring now to FIG. **3**, a system **300** is shown that performs concurrent reference counting garbage collection in accordance with one embodiment of the present invention. System **300** comprises three processors **310**, **320**, and **330** that operate in parallel and independently, and shared memory **380**. Processors **310**, **320**, and **330** can each access shared memory **380**. Processor **310** comprises a mutator **313** that keeps track of increments **317** and decrements **319** to objects (not shown) on processor **310** The increments **317** and decrements **319** are stored in mutator buffet **314** for this purpose. Similarly, processor **320** comprises a mutator **323** that keeps track of increments **327** and decrements **329** to objects (not shown) on computer system **320**. The increments **327** and decrements **329** are stored in a mutator buffer **324** for this purpose. Processor **330** comprises a garbage collector **340** that keeps track of decrements from a previous epoch **345**, increments from a current epoch **350**, decrements from a current epoch **355**, root buffer **360**, and cycle buffer **370**. As shown, each processor includes some type of memory that is used to store its respective processes and data.

[0037] Periodically, mutator **313**, **323** sends the contents of its mutator buffer **314**, **324** to garbage collector **340**. This occurs once each epoch. At the beginning of an epoch, the garbage collector **340** applies the increments from the current epoch **350**. Then the garbage collector **340** applies the decrements from the previous epoch **345**. During this process, the garbage collector **340** modifies root buffer **360**. The garbage collector **340** stores the decrements from the current epoch in location **355**. During the next epoch, these decrements will be applied.

[0038] After the increments for the current epoch **350** and decrements for the previous epoch **345** have been applied, the garbage collector **340** will perform concurrent garbage collection. Concurrent garbage collection is described in more detail in reference to FIG. **5**. What is important to note is that mutators **313** and **323** act independently from themselves and from garbage collector **340**. Therefore, while garbage collector **340** is modifying reference counts of objects, mutators **313** and **323** may be adding references to these objects or removing references from these objects. Moreover, because the mutators only periodically send changes to reference counts to the garbage collector **340**, the garbage collector **340** has to act within the confines of this delayed notice. Techniques for garbage collection under these circumstances must take these conditions into account. It is also important to note that, while mutators **313**, **323** keep track of reference addition and deletions, only the garbage collector **340** is allowed to modify the reference count for objects.

[0039] It should be noted that the data in each computer system may be separately stored from the software operating on it. For example, the mutator buffer **314** is shown as part of mutator **313**, but mutator buffer **314** could be stored separately from mutator **313**. FIG. **3** is depicted to aid understanding. It should also be noted that each processor **310**, **320**, and **330** could be part of a separate computer system, and that portions or all of what is shown for each processor may be stored in shared memory **380** For example, mutator **313** may be stored in shared memory **380** and moved from shared memory **380** into memory (e. g., L**1** or L**2** cache) in processor **310** when the mutator **313** is executed.

[0040] Turning now to FIG. **4**, a diagram is shown of execution timelines for three processors. There are three

timelines shown: a timeline **410** that corresponds to processor **310** of FIG. **3**; a timeline **420** that corresponds to processor **320** of FIG. **3**; and a timeline **430** that corresponds to processor **330** of FIG. **3**, FIG. **4** also helps to illustrate and describe epochs.

[**0041**] Timeline **410** comprises areas **411**, **412**, **413**, and **414** where processes or threads are executed, and interruptions **415**, **416** and **417** by a garbage collector thread running on that computer system. Similarly, timeline **420** comprises areas **421**, **422**, **423**, and **424** where processes or threads are executed, and interruptions **425**, **426** and **427** by a collector thread running on that computer system. Timeline **430** comprises areas **431**, **432**, **433**, and **434**, where processes or threads are executed. Periods **435**, **436**, and **437** are times when the garbage collector executes.

[**0042**] As previously discussed, the mutators produce operations on reference counts, which are placed into buffers and periodically turned over to the garbage collector (also called "collector" herein), which runs on its own processor. The collector is single-threaded, and is the only thread in the system which is allowed to modify the reference count fields of objects. Generally, a collector thread actually transmits the contents of the mutator buffer. Thus, the mutator creates increments and decrements and a collector thread sends the contents of the mutator buffer to a garbage collector running on its own processor.

[**0043**] For example, during interrupt **415**, a collector thread sends the contents of the mutator buffer created on processor **310** (not shown), which creates timeline **410**, to the garbage collector. The garbage collector runs on processor **330**, which creates timeline **430**. During interrupt **425**, a second collector thread sends the contents of the mutator buffer created on processor **320** (not shown), which creates timeline **420**, to the garbage collector. The garbage collector then runs in period **435**.

[**0044**] During mutator operation, updates to the stacks are not reference-counted. Only heap updates are reference-counted, and those operations are deferred with a write barrier by storing the addresses of objects whose counts must be adjusted into mutation buffers, which contain increments or decrements. Objects are allocated with a reference count of one, and a corresponding decrement operation is immediately written into the mutation buffer. In this manner, temporary objects never stored into the heap are collected quickly.

[**0045**] As has been discussed, time is divided into epochs, which are separated by collections that comprise each processor briefly running its collector thread. In FIG. **4**, epochs **440**, **450**, **460** and **470** are shown. These epochs are determined from the point of view of timeline **430**. Epoch boundaries are staggered, the only restriction being that all processors must participate in one collection before the next collection can begin. Periodically, some event will trigger a collection cycle. This trigger could occur because a certain amount of memory has been allocated, because a mutation buffet is full, or because a timer has expired. In normal operation, none of these triggers will cause the mutator to block; however, they will schedule the collector thread to run on the first processor.

[**0046**] On the first processor, when the collector thread wakes up, it scans the stacks of its local threads and places the addresses of objects in the stack into a stack buffer. It then increments its local epoch number, allocates a new mutation buffer, and schedules the collector thread on the next processor to run. Finally, it dispatches to the thread that was interrupted by collection. The collector thread performs these same operations for each processor until it reaches the last processor. The last processor actually performs the work of collection.

[**0047**] This is shown in FIG. **4**, where timeline **410** periodically runs a collector thread in interrupts **415**, **416**, and **417** and where timeline **420** periodically runs a collector thread in interrupts **425**, **426**, and **427**. The garbage collector then runs on the last processor, processor **330** that creates timeline **430**, in periods **435**, **436**, and **437**.

[**0048**] The last processor scans the stacks of its local threads into a stack buffer. Then it processes increments in the following manner. The reference count of each object addressed in the stack buffer, for the current epoch computed by each processor, is incremented. Then the mutator buffer for each processor for the current epoch is scanned, and the increment operations it contains are performed.

[**0049**] To avoid race conditions that might cause the collector to process a decrement before the corresponding increment has been processed, the increment operations are processed first and the decrement operations are processed one epoch behind. So the last processor scans the stack buffers of the previous epoch, and decrements the reference counts of objects that they address, and then processes the mutation buffers of the previous epoch, performing the decrement operations.

[**0050**] During the decrement phase, any object whose reference count drops to zero is immediately freed, and the reference counts of objects it points to are recursively decremented. Finally, the stack and mutation buffers of the previous epoch are returned to the buffer pool, and the epoch number is incremented. The collection has finished and all processors have joined the new epoch, and now any processor can trigger the next collection phase.

[**0051**] The reason for processing increments of the current epoch and delaying decrements one epoch is shown in FIG. **4**. Assume that increments and decrements are processed as they arrive. Assume, at time **480**, that a mutator running in timeline **410** increments a reference to an object. This increment will be sent to the garbage collector during interrupt **417**. Also assume that, at the same time **480**, a mutator running in timeline **420** decrements a reference to the same object. This decrement will be sent to the garbage collector during interrupt **426** This means that the garbage collector could, if the decrement is immediately processed, decrement the reference count for this object during period **436**. If the reference count for the object drops to zero or if the reference count is positive but the object is part of a cycle, the object will be collected as garbage in period **436**.

[**0052**] However, the object should not be garbage because the mutator running in timeline **410** has incremented the reference count to the object. This increment will not be processed until it is sent in interrupt **417** and until the garbage collector runs in period **437**. Thus, increments from the current epoch are performed first and decrements from a previous epoch are performed last. In the previous scenario, this means that the decrement at time **480** would not be

processed until period **437** and also after the increment has been processed in period **437**.

[**0053**] Note that the definitions of epoch as used herein mean that part of each period **435**, **436**, and **437** performs the decrements and increments to the reference counts. This part is in one epoch, while the part of each period **435**, **436**, and **437** that performs cyclic garbage collection is in another epoch. Using this definition, an increment that occurs in epoch **450** is acted upon in epoch **450**. Other definitions may be used, and the definition above is used herein solely to maintain consistent terminology. For instance, all of periods **435**, **436**, and **437** could be considered as part of a current epoch. Using this definition, increments from the immediately proceeding epoch are applied, then decrements from two epochs ago are applied. In FIG. **4**, in period **437**, increments from epoch **460** are applied and then decrements from period **450** are applied. What is important is that an increment created by one processor before its collection period occurs will be processed prior to processing a decrement created by another (or the same) processor before two of its collection periods have occurred.

[**0054**] Referring now to FIG. **5**, a method **500** is shown for concurrent garbage collection of cyclic data structures in a reference counting computer system, in accordance with one embodiment of the present invention. Method **500** is performed by a garbage collector after increments and decrements from the current epoch have been transmitted by all of the processors in a system. Method **500** is preferably performed once each epoch and starts, as indicated in step **505**, at the epoch boundary.

[**0055**] Thus, prior to step **505**, the increments and decrements for the current epoch have been sent by processors in the system. Additionally, other steps are taken in step **505**, such as allocating memory and scanning stack buffers.

[**0056**] In step **510**, the increments and decrements from all of the processors are retrieved, generally from shared memory. In step **515**, increments from the current epoch are applied, and, in step **520**, decrements from the previous epoch are applied. As discussed above, delaying processing of decrements for one epoch ensures that increments will be added before decrements. This prevents the possibility of a cycle from being removed if an increment occurs after a decrement.

[**0057**] In step **525**, non-cyclic garbage is removed, which means that any object whose reference count is zero is collected as garbage. In step **530**, decrements from the current epoch are stored. These will be used the next time method **500** is run. At that time (i e., an epoch later), these will be decrements from a previous epoch.

[**0058**] As with other concurrent garbage collection algorithms, method **500** must contend with the fact that the object graph may be modified simultaneously with the scanning of it by the garbage collector. In addition, the reference counts may be as much as a two epochs out of date (because decrements are deferred by an epoch).

[**0059**] Method **500** relies on the same basic premise as the synchronous algorithm described in the filed application entitled "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," which has been incorporated by reference above. This premise is that given a subset of nodes, if deleting the internal edges between the nodes in this subset reduces the reference count of every node in the subset to zero, then the whole subset of nodes is cyclic garbage. The subset may represent more than one independent cycle, but all of the cycles in the subset are all garbage cycles.

[**0060**] However, since the graph may be modified, there are three basic difficulties. Firstly, since one cannot rely on being able to retrace the same graph, the repeated traversal of the graph does not always define the same set of nodes. Secondly, the deletion of edges can disconnect portions of the graph, thus making the global test by graph traversal difficult. Thirdly, reference counts may be out of date.

[**0061**] To deal with these difficulties, the cyclic garbage collection portion of method **500** proceeds in two phases. In the first phase, a candidate set of garbage nodes is discovered. Then method **500** waits until an epoch boundary and performs the second phase in which tests are performed to ensure that the candidates do indeed satisfy the criteria for garbage cycles.

[**0062**] The two phases can be viewed as enforcing a "liveness" and a "safety" property. The first phase enforces liveness by ensuring that potential garbage cycles are considered for collection. The second phase ensures safety by preventing the collection of false cycles induced by concurrent mutator activity. The liveness phase is performed by steps **550** through **580**, while the safety phase is performed by steps **535** and **540** Before discussing the liveness and safety phases, it is worthwhile to note that certain steps of method **500** may not be performed for every epoch. For example, the first time method **500** is run, steps **510** through **545** may not be performed if there are no increments or decrements. If there are increments and decrements the first time method **500** is performed, step **520** will not be performed because there is no "previous" epoch. Additionally, if there are no candidate cycles after step **525** is performed, then steps **535** through **545** need not be performed. The following discussion assumes that no candidate cycles remain after step **525**, such that steps **535** through **545** need not be performed. This assumption is made simply to enable description of the liveness phase prior to description of the safety phase of method **500**.

[**0063**] The liveness phase comprises steps **550** through **580**. In step **550**, candidate cycles are determined through the use of a synchronous garbage collection algorithm. The synchronous method described in "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," incorporated by reference above, may be used to find candidate cycles. Alternatively, other reference counting methods may be used to find candidate cycles. Finding and marking candidate cycles occurs in step **550**. Candidate root nodes are initially marked as purple and stored in a root buffer. During step **550**, the loot nodes are used to search cycles, and cycles that are possibly garbage are collected and placed into a cycle buffer (referred to as a "CycleBuffer" herein). The objects in the cycle buffet are colored orange.

[**0064**] As previously discussed, due to concurrent mutator activity, the graph may be changing and a synchronous method of garbage collection may produce incorrect results. To perform concurrent cycle collection, a second reference count for each object, denoted CRC(S), is created. This occurs in step **555**. The Cyclic Reference Count (CRC) is a hypothetical reference count that may become incorrect due

to concurrent mutator activity. In one embodiment, the reference counts, the cyclic reference count, the color, and a buffered flag are placed into a single header word by using a hash table to hold count overflows, which occur very rarely. The buffered flag is described in "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," and its use is optional but beneficial. The liveness phase of the concurrent method **500** proceeds in a similar manner to the synchronous cycle collection method described in "Synchronous Collection of Cyclic Garbage in Reference Counting Systems." However, in the concurrent method **500**, when an object is marked gray, its cyclic reference count is initialized to its true reference count and the "true" reference count is not changed. The cyclic reference count is created in step **555**. Henceforward, the mark, scan, and collect phases, of the synchronous cycle collection method described in "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," operate upon the cyclic reference count instead of the true reference count.

[**0065**] By using the cyclic reference count, it is ensured that, in the event of concurrent mutator activity, the information about the true reference count of the objects is never lost. In absence of mutator activity, the liveness phase will yield the set of garbage nodes, and the safety phase will certify that this indeed is a set of garbage of nodes and these garbage nodes can be collected.

[**0066**] However, the presence of concurrent mutator activity can cause live nodes to enter the list in three different ways. Firstly, the mutator can add an edge, thus causing the marking procedure of the synchronous method to incorrectly infer that there are no external edges to a live object. Secondly, the mutator can delete an edge, thus causing the scan procedure of the synchronous method to incorrectly infer a live object to be garbage. Thirdly, the deletion of edges concurrent to running of the marking and scanning procedure can create gray and white nodes with various values of cyclic reference counts. While eventually the reporting of the mutator activity will cause these nodes to be detected and re-colored, if these nodes are encountered before they are re-colored, they can mislead the runs of the above procedures into inferring that they are garbage.

[**0067**] Another step in the liveness phase is a Σ-preparation step, which is step **560**. In the Σ-preparation step **560**, which is preferably performed immediately after the candidate cycles have been found, each subset in the CycleBuffer is iterated over and the cyclic reference count of every node in the subset is initialized to the reference count of the node. Then every node in the subset is iterated over again and the cyclic reference count of any children of the node that are also in the subset are decremented. At the end of the Σ-preparation computation, the cyclic reference count of each node in the subset represents the number of references to the node from nodes external to the subset. Step **580** effectively computes external reference counts for each object. In step **580**, method **500** ends until the next epoch boundary occurs. In this step, such functions as deallocating memory and returning control to the operating system may be performed.

[**0068**] The output of the liveness phase is a set of nodes believed to be garbage and placed in a CycleBuffer data structure. The job of the liveness phase can be seen as finding likely sets of candidates for garbage cycles. If the mutator activity is small in a given epoch, this would indeed be very likely to be true. The CycleBuffer is divided into discrete connected components, each of which forms a potential garbage cycle. This is explained in more detail in reference to FIG. **6**. Due to mutator activity, the contents of the CycleBuffer can be a superset of the actual set of garbage nodes and can contain some nodes that fail tests in the safety phase.

[**0069**] Assume now that the next epoch boundary has occurred, that steps **505** through **530** have been performed, and that the CycleBuffer is not empty. At this point, the second phase of the algorithm is performed. The second phase of the algorithm will now be described.

[**0070**] The second ("safety") phase of the algorithm takes, as input, a set of nodes and determines whether they form a garbage cycle. These nodes have already been marked with a special color, orange, which is used to identify a candidate set in the concurrent cycle collector. The safety phase of method **500** comprises two tests called the Δ-test and the Σ-test. The Δ-test is performed in step **535**, and the Σ-test is performed in step **540**. If a subset of nodes of the object graph passes both the Δ-test and the Σ-test, then it is assured that the nodes in the subset are all garbage. Thus, correctness of the safety phase of method **500** is not determined by any property of the output of the liveness phase which selects the subgraphs. This property of the safety phase of the algorithm considerably simplifies the proof of correctness as well as modularizing the code.

[**0071**] In step **535**, the Δ-test is performed. This test ensures that no new reference was added to an object in a cycle. Because mutator activity can occur in parallel with garbage collection, the reference count used during the running of the preparation procedure may be outdated due to an inclement to one of the nodes in a subset in the CycleBuffer. Any increments are ascertained by the Δ-test in step **535**. It should be noted that, in step **515**, increment processing will re-color black all non-black nodes and their reachable subgraphs. Then it is determined if the candidates are still garbage in step **535**. To do this, the nodes in the candidate set are scanned and are tested to determine whether their colors are still orange. If they are all orange, there has been no inclement to the reference count since the running of the preparation procedure (step **560**) and the candidate set passes the Δ-test. Any cycle or object that fails the test is removed from the CycleBuffer in step **535**.

[**0072**] The Σ-test, as part of the safety phase of method **500**, ensures that all references to objects in a set are from objects within the set. In the Σ-test, which is performed in step **540**, every node in the subset is iterated over and every node is tested to determine if its cyclic reference count is zero. If the cyclic reference count is zero for every member of the set, then it is known that there exists no reference to this subset from any other node. Therefore, any candidate set that passes the Σ-test is garbage, unless the reference count used during the running of the preparation procedure is outdated due to an inclement to one of the nodes in the subset. However, the Δ-test, performed in step **535**, has already been performed and has removed any cycle of node whose reference count is outdated due to an increment. In step **540**, any cycle that fails the Σ-test is not garbage and is removed from the CycleBuffer.

[**0073**] Any subset of garbage nodes that does not have any external pointers to it will pass both the Δ-test and the Σ-test.

Note that method **500** does not have to be concerned with concurrent decrements to the members of the subset, since it is not possible fox the reference count of any node to drop below zero. However, it is possible for a set of garbage to have pointers to it from other garbage cycles. It is also known that the garbage cycles in the cycle buffer cannot have any forward pointers to other garbage cycles (if they did, method **500** would have followed them and included them in a previous garbage cycle). Hence, the candidate cycles are processed in the cycle buffer in the reverse of the order in which they were found. This reasoning is described in reference to FIG. **6**

[**0074**] When a candidate set passes both tests, and hence is determined to be garbage, then the nodes in the cycle are collected and freed (step **545**), which causes the reference counts of other nodes outside of the cycle to be decremented. By the stability property of garbage, one can decrement such reference counts without concern for concurrent mutation. When a reference count to an orange node is decremented, its cyclic reference count is also decremented. Therefore, when the next candidate cycle is considered (the previous cycle in the buffer), if it is garbage the Δ-test will succeed because the computation has been augmented by the preparation procedure (step **560**). Hence, when a candidate set is reached, the cyclic reference count does not include the count of any pointers from a known garbage node. This ensures that all the nodes in would be collected.

[**0075**] Method **500** continues with steps **550** through **560**, which have already been described. The method ends, until the next epoch, in step **580**.

[**0076**] Turning now to FIG. **6**, a block diagram is shown of the creation of a cycle buffer **660** from a root directory **600** for one particular subgraph **630**, in accordance with one embodiment of the present invention. Root buffer **600** comprises root nodes **610**, **615**, and **620**, which contain references to objects **635**, **640**, and **645**, respectively. Subgraph **630** comprises three objects **635**, **640**, and **645** As described in "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," an object may be a root of cyclic garbage if the reference count for the object is decremented to a non-zero value. In this example, which is a worst-case example for cyclic garbage collection, all three objects have had their reference counts decremented and are placed in root buffer **600** as shown. This subgraph **630** is garbage.

[**0077**] Cycle buffer **660** comprises complete cycles that may be garbage. In this case, there are three cycles **665**, **670**, and **675** Each cycle in cycle buffer **660** is cleated and determined from a cycle defined by a root node in root buffer **600**. For example, root node **610** contains a reference to object **635**, and object **635** describes a subgraph that comprises one object, itself. Cycle **665** therefore contains a reference to object **635**. Root node **615** contains a reference to object **640**, which describes a subgraph comprised of two objects, objects **640** and **630** Consequently, cycle **670** comprises references to objects **640** and **635**. Finally, root node **620** comprises a reference to object **645**, which describes subgraph **630** comprising objects **645**, **640**, and **635**. Therefore, cycle **675** comprises references to objects **645**, **640**, and **635**.

[**0078**] Cycle buffer **660** allows cycles to be easily and quickly determined and searched. It does this at the expense of memory. However, because cyclic garbage collection can be time-consuming, memory tends to be less important than time.

[**0079**] If the safety tests of the present invention were performed in the order of cycle **665**, **670**, and then **675** (i.e., the order in which the cycles are added to the cycle buffer), an inefficiency occurs. Object **635** would be examined three times, once for each cycle **665**, **670**, and **675**, while object **640** would be examined twice, once for each cycle **670** and **675**, and object **645** would be examined once for cycle **675**. To prevent this inefficiency, the cycles are examined in the reverse order, starting with cycle **675** and ending with cycle **665**. In this situation, at the end of performing the safety tests on cycle **675**, objects **635**, **640**, and **645** would be freed, thereby obviating the performance of the safety tests for cycles **670** and **665**. This saves several steps in computation.

[**0080**] Referring now to FIG. **7**, a state transition graph is shown for concurrent garbage collection of cyclic data structures in a reference counting computer system, in accordance with one embodiment of the present invention. All objects start as black. As previously described, the meanings of the colors used herein are as follows: black indicates that a node is "in use" or "free"; gray indicates that a node is a possible member of a cycle; white indicates that a node is a member of a cycle; purple indicates a possible root of a cycle; orange indicates that the object is part of a candidate cycle awaiting an epoch boundary; and red indicates that the object is part of a candidate cycle undergoing a Σ-computation.

[**0081**] If the state is black, increments to the reference count and decrements of the reference count to zero do not change the state. A decrement of the reference count to a non-zero value will cause the object to be colored purple. While in the purple state, a decrement to the reference count to a non-zero value does not change the state. A decrement to zero or an increment will change the color to black. When method **500** of FIG. **5** performs the liveness phase of garbage collection, it will mark purple objects as gray if they have been examined.

[**0082**] If state is black, method **500** of FIG. **5** will change the color from black to gray during the marking phase, When the object is gray, a scan will cause the object to be marked white. A scan occurs during the scanning phase, when the object has a zero reference count. Increments, decrements, and an unscan will cause the object to be changed from gray to black. An increment and decrement are possible during concurrent mutator operation. An unscan occurs when it is determined that a cycle is not garbage.

[**0083**] If the object is white, a flee operation, which returns the object to the heap, will mark the object as black. Additionally, increments, decrements, and unscan operations will cause the white object to be marked black. Increments and decrements are caused by concurrent mutator operation. An unscan operation occurs if a member of garbage cycle really is not garbage. For example, if an increment operation has incremented the reference count of an object in a cycle, one of the safety tests will determine this and mark black all other white objects in the cycle.

[**0084**] White objects can be collected, which means that they are marked orange. If a free operation or an increment operation occurs, the orange object is marked black. This

can occur in the Δ-test. The Σ preparation marks an orange object red. Red is used to mark objects that belong to a particular candidate cycle.

[0085] Turning now to FIGS. **8** and **9**, exemplary listings of pseudocode instructions are shown that may be used to implement concurrent garbage collection of cyclic data structures in a reference counting computer system, in accordance with one embodiment of the present invention. The pseudocode is explained below.

[0086] The operation of CollectCycles and its subsidiary procedures is very similar to the operation of the synchronous algorithm of "Synchronous Collection of Cyclic Garbage in Reference Counting Systems," called the "synchronous algorithm" herein, so for those procedures only the differences will be focused on here.

[0087] Increment(S): The true reference count is incremented Since the reference count is being incremented, the node must be live, so any non-black objects reachable from it are colored black by invoking ScanBlack. This has the effect of re-blackening live nodes that were left gray or white when concurrent mutation interrupted a previous cycle collection.

[0088] Decrement(S): At the high level, decrementing looks the same as with the synchronous algorithm: if the count becomes zero, the object is released, otherwise it is considered as a possible root.

[0089] PossibleRoot(S): For a possible root, first ScanBlack is performed. As with Increment, this has the effect of re-blackening leftover gray or white nodes. It may also change the color of some purple nodes reachable from S to black, but this is not a problem since they will be considered when the cycle collector considers S. The rest of PossibleRoot is the same as for the synchronous algorithm.

[0090] ProcessCycles(): Invoked once per epoch after increment and decrement processing due to the mutation buffers from the mutator threads has been completed. First, FreeCycles attempts to flee candidate cycles discovered during the previous epoch. Then CollectCycles collects new candidate cycles and SigmaPreparation prepares for the Σ-test to be run in the next epoch.

[0091] CollectCycles(): As in the synchronous algorithm, three phases are invoked on the candidate roots: marking, scanning, and collection.

[0092] MarkRoots(): This procedure is the same as in the synchronous algorithm.

[0093] ScanRoots(): This procedure is the same as in the synchronous algorithm.

[0094] CollectRoots(): For each remaining root, if it is white a candidate cycle has been discovered starting at that root. The CurrentCycle is initialized to be empty, and the CollectWhite procedure is invoked to gather the members of the cycle into the CurrentCycle and color them orange. The collected cycle is then appended to the CycleBuffer. If the root is not white, a candidate cycle was not found from this root or it was already included in some previously collected candidate, and the buffered flag is set to false. In either case, the root is removed from the Roots buffer, so that at the end of this procedure the Roots buffer is empty.

[0095] MarkGray(S): This is similar to the synchronous version of the procedure, with adaptations to use the cyclic reference count (CRC) instead of the true reference count (RC). If the color is not gray, it is set to gray and the CRC is copied from the RC, and then MarkGray is invoked recursively on the children. If the color is already gray, and if the CRC is not already zero, the CRC is decremented (the check for non-zero is necessary because concurrent mutation could otherwise cause the CRC to underflow).

[0096] Scan(S): As with MarkGray, simply an adaptation of the synchronous procedure that uses the CRC. Nodes with zero CRC are colored white; non-black nodes with CRC greater than zero are recursively re-colored black.

[0097] ScanBlack(S): Like the synchronous version of the procedure, but it does not need to re-increment the true reference count because all reference count computations were carried out on the CRC.

[0098] CollectWhite(S): This procedure recursively gathers white nodes identified as members of a candidate garbage cycle into the CurrentCycle and colors them orange as it goes. The buffered flag is also set true since a reference to the node will be stored in the CycleBuffer when CurrentCycle is appended to it.

[0099] SigmaPreparation(): After the candidate cycles have been collected into the CycleBuffer, this procedure prepares for the execution of the Σ-test in the next epoch. It operates individually on each candidate cycle C. First, each node S in C has its CRC initialized to its RC and its color set to red. After this only the nodes of C are red. Then for any pointer from one node in C to another node in C, the CRC of the target node is decremented. Finally, the nodes in C are re-colored orange. At the end of SigmaPreparation, the CRC field of each node S contains a count of the number of references to S from outside of C.

[0100] FreeCycles(): This procedure iterates over the candidate cycles in the reverse order in which they were collected. It applies the safety tests (the Σ-test and the Δ-test) to each cycle and if it passes both tests then the cycle is freed. Otherwise it is refurbished, meaning that it may be reconsidered for collection in the next epoch.

[0101] DeltaTest(C): This procedure returns true if the color of all nodes in the cycle awe orange, which indicates that their have been no increments to any of the nodes in the cycle

[0102] SigmaTest(C): This procedure calculates the total number of external references to nodes in the cycle, using the CRC fields computed by the SigmaPreparation procedure. It returns true if the number of external references is zero, false otherwise.

[0103] Refurbish(C): If the candidate cycle has not been collected due to failing a safety test, this procedure re-colors the nodes. If the first node in the candidate cycle (which was the purple node from which the candidate was found) is still orange, or if any node has become purple, then those nodes are colored purple and placed in the Roots buffer. All other nodes are colored black and their buffered flags are cleared

[0104] FreeCycle(C): This procedure actually frees the members of a candidate cycle that has passed the safety tests First, the members of C are colored red; after this, only the

nodes in C are red. Then for each node S in C, CyclicDecrement decrements reference counts in non-red nodes pointed to by S.

[0105] CyclicDecrement(M): If a node is not red, then it either belongs to some other candidate cycle or not. If it belongs to some other candidate cycle, then it is orange, in which case both the RC and the CRC fields are decremented (the CRC field is decremented to update the computation performed previously by the SigmaPreparation procedure to take the deletion of the cycle pointing to M into account). If it does not belong to some other candidate cycle, it will not be orange and a normal Decrement operation is performed.

[0106] For ease of presentation, the pseudocode has been presented in a way that maximizes readability. However, this means that, as presented, the code makes more passes over the nodes than is strictly necessary. For instance, the first pass by SigmaPreparation can be merged with CollectWhite, and the passes performed by DeltaTest and SigmaTest can be combined. In this implementation, the passes are combined to minimize constant-factor overheads.

[0107] FIGS. **10** and **11** are diagrams of cyclic data structures and possible concurrent operations that can possibly create inaccuracies if both tests of the present invention are not performed. FIG. **10** illustrates a race condition uniquely detected by the Σ-test, while FIG. **11** illustrates a race condition uniquely detected by the Δ-test

[0108] Referring now to FIG. **10**, a subgraph **1000** is shown that contains objects **1010**, **1020**, **1030**, **1040**, and **1050**. Subgraph **100** is a cycle, but not a garbage cycle. The subgraph **1000** is described by a root entered in the root buffer because object **1010** has a decrement to its reference count that is not to zero. Each object has two counts: the top count is the reference count; and the bottom count is the cyclic reference count.

[0109] This cycle was detected from the purple node **1010**, which is the starting point from which cycle collection is run. If the edge between nodes **1030** and **1040** is cut (indicated by cut **1060**) between the MarkGray and the Scan routines, then the nodes **1010** and **1020** will be collected by the CollectWhite routine and form a cycle. These nodes are not garbage. However, since there have been no increments to the reference counts of either of these nodes, this set will pass Δ-test. The decrements will be processed an epoch later, at epoch i+1, so the decrement to node **1040** will not have an effect on the nodes **1010** and **1020** in the FreeCycles operation performed in epoch i. Even waiting fox an additional epoch does not guarantee that the fact that nodes **1010** and **1020** will be detected by Δ-test, since during epoch i the edge from node **1040** to node **1050** could be cut. Indeed, by making the chain of nodes {**1030**, **1040**, **1050**} be arbitrarily long and having a malicious mutator cut edges at just the tight moment, it is possible to have the non-garbage cycle of nodes pass the Δ-test for arbitrarily many epochs. Hence the Δ-test alone cannot detect all live nodes in the set of a candidate cycles.

[0110] Now consider the subgraph **1100** of nodes **1110**, **1120**, and **1130** shown in FIG. **11**. The cycle is detected starting with the purple node **1110**, from which cycle collection is run. If a new edge is added from node **1130** to node **1120** (as noted by edge **1140**) before the MarkGray routine is run, the reference count of the node **1120** will be out of date. If the cycle collector observes the newly added edge, the sum of the reference counts in {**1110**, **1120**, **1130**} will equal the sum of the edges. Hence the set of nodes {**1110**, **1120**, **1130**} will be collected by the CollectWhite routine and form a candidate cycle. If the increments are not processed before the Σ-test is done, then this candidate cycle will pass the Σ-test. Hence the Σ-test alone cannot detect all live nodes in the set of candidate cycles.

[0111] Notice that it is not claimed that the two race conditions shown in FIG. **10** and **11** are an exhaustive list of all possible race conditions the present invention will face. But these two are sufficient to show the necessity of both the tests. Thus, the two tests are both necessary and sufficient to ensure the safety of the algorithm. That both tests are necessary and sufficient is proven in Bacon et al., "Concurrent Cycle Collection in Reference Counting Systems," Proc. European Conf. on Object-Oriented Programming, Lecture Notes in Computer Science (LNCS), vol. 2072 (2001), the disclosure of which is incorporated herein by reference.

[0112] Turning now to FIG. **12**, a block diagram is shown of an exemplary system **1200** suitable for carrying out embodiments of the present invention. System **1200** comprises a computer system **1210** and a Compact Disk (CD) **1250**. Computer system **1210** comprises N processors **1220-1** through **1220**-N (collectively, "processors **1220**"), a memory **1230** and an optional video display **1240**.

[0113] As is known in the art, the methods and apparatus discussed herein may be distributed as an article of manufacture that itself comprises a computer-readable medium having computer-readable code means embodied thereon. The computer-readable program code means is operable, in conjunction with a computer system such as computer system **1210**, to carry out all or some of the steps to perform the methods or create the apparatuses discussed herein. The computer-readable medium may be a recordable medium (e g., floppy disks, hard drives, compact disks, such as CD **1250**, or memory cards) or may be a transmission medium (e g., a network comprising fiber-optics, the world-wide web, cables, or a wireless channel using time-division multiple access, code-division multiple access, or other radio-frequency channel). Any medium known or developed that can store information suitable for use with a computer system may be used. The computer-readable code means is any mechanism for allowing a computer to read instructions and data, such as magnetic variations on a magnetic medium or height variations on the surface of a compact disk, such as compact disk **1250**.

[0114] Memory **1230** configures the processor **1220** to implement the methods, steps, and functions disclosed herein. The memory **1230** could be distributed or local and the processor **1220** could be distributed or singular. The memory **1230** could be implemented as an electrical, magnetic or optical memory, or any combination of these or other types of storage devices. Moreover, the term "memory" should be construed broadly enough to encompass any information able to be read from or written to an address in the addressable space accessed by processor **1210**. With this definition, information on a network is still

within memory **1230** because the processor **1220** can retrieve the information from the network. It should be noted that each distributed processor that makes up processor **1220** generally contains its own addressable memory space. It should also be noted that some or all of computer system **1210** can be incorporated into an application-specific or general-use integrated circuit.

[**0115**] Optional video display **1240** is any type of video display suitable for interacting with a human user of system **1200**. Generally, video display **1240** is a computer monitor or other similar video display

[**0116**] It is to be understood that the embodiments and variations shown and described herein are merely illustrative of the principles of this invention and that various modifications may be implemented by those skilled in the art without departing from the scope and spirit of the invention.

What is claimed is:

1. A method useful for concurrent collection of cyclic garbage in a reference counting system, the method comprising the steps of:

identifying candidate objects having associated reference counts for garbage collection, wherein each candidate object is potentially garbage; and

determining if the candidate objects are garbage, the step of determining performed without preventing mutators in the system from changing object references and the step of determining further comprising the steps of:

determining, after a time period, if the candidate objects are still potentially garbage; and

for those candidate objects that are still potentially garbage, determining if the reference count associated with the candidate object has changed.

2. The method of claim 1, wherein:

wherein each candidate object is potentially garbage;

the step of determining if the candidate objects are garbage further comprises the steps of:

determining, after a time period, if the candidate objects are still potentially garbage; and

for those candidate objects that are still potentially garbage, determining if the reference count associated with the candidate object has changed.

3. The method of claim 1, wherein the step of determining if the reference count associated with the candidate object has changed further comprises the step of determining, after a time period, if the reference count associated with the candidate object has changed.

4. The method of claim 3, wherein:

the step of determining, after a time period, if the candidate objects are still potentially garbage further comprises the step of for each candidate object, copying a reference count associated with the object into a cyclic reference count; and

the step of determining, after a second time period, if the reference count associated with the candidate object has changed further comprises the step of determining, for each candidate object if the cyclic reference count is zero.

5. The method of claim 4, wherein:

the step of finding candidate objects for garbage collection comprises the steps of:

determining root objects by determining objects whose reference count has been decremented to a non-zero value;

for each root object, determining objects in a cycle defined by the root object;

storing references to each object in a cycle, thereby storing each cycle; and

the step of determining, after a second time period, if the reference count associated with the candidate object has changed further comprises the step of processing the cycles in reverse order of an order in which they were stored.

6. The method of claim 3, wherein the time period is an epoch.

7. The method of claim 1, wherein each candidate object is part of a cycle and wherein the step of determining, after a time period, if the candidate objects are still potentially garbage comprises the steps of:

for each candidate object, copying a reference count associated with the object into a cyclic reference count;

for each candidate object, decrementing the cyclic reference count each time a reference from a referencing object refers to the candidate object, wherein the referencing object resides in the cycle in which the candidate object resides;

waiting the time period; and

for each candidate object, determining if the cyclic reference count associated with the candidate object is zero.

8. The method of claim 1, wherein:

the step of identifying candidate objects for garbage collection further comprises the steps of:

identifying a plurality of roots for garbage collection, wherein each root comprises a reference count and wherein each root describes a set comprising objects that are interconnected through references;

selecting one of the sets;

performing the following steps for the set:

for each object in the set, creating a copy of the reference count; and

for each object in the set, decrementing the copy of the reference count associated with the object for as many times as the object is referenced by itself or another object contained in the set;

the step of determining further comprises:

determining, after a time period, if the copies of the reference counts for each object in the set are zero;

determining if one or more increments have made at least one reference count for objects in the set outdated; and

collecting the set as garbage when the copies for each object in the set are zero and when there are no outdated reference counts.

9. The method of claim 8, wherein the time period is an epoch.

10. A method for processing changes to reference counts in a reference counting system, each reference count associated with a particular object and containing a number of references that reference the particular object, the method comprising the steps of:

determining increments and decrements of reference counts for a current time period;

processing the increments of reference counts for the current time period;

storing the decrements of reference counts for the current time period; and

processing decrements of reference counts for a previous time period.

11. The method of claim 10, wherein each of the current and previous time periods are an epoch.

12. The method of claim 11, wherein each epoch is separated by a period where increments and decrements to reference counts are applied for all processors in a plurality of processors.

13. A computer system comprising:

a memory that stores computer-readable code; and

a processor operatively coupled to the memory, the processor configured to implement the computer-readable code, the computer-readable code configured to:

identify candidate objects having associated reference counts for garbage collection, wherein each candidate object is potentially garbage; and

determine if the candidate objects are garbage, the step of determining performed without preventing mutators in the system from changing object references and the step of determining further comprising the steps of:

determining, after a time period, if the candidate objects are still potentially garbage; and

for those candidate objects that are still potentially garbage, determining if the reference count associated with the candidate object has changed.

14. An article of manufacture comprising:

a computer-readable medium having computer-readable program code means embodied thereon, the computer-readable program code means comprising:

a step to identify candidate objects having associated reference counts for garbage collection, wherein each candidate object is potentially garbage; and

a step to determine if the candidate objects are garbage, the step of determining performed without preventing mutators in the system from changing object references and the step of determining further comprising the steps of:

determining, after a time period, if the candidate objects are still potentially garbage; and

for those candidate objects that are still potentially garbage, determining if the reference count associated with the candidate object has changed.

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