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(54) METHOD FOR MANAGING CONCURRENT PROCESSES USING DUAL LOCKING

(76) Inventors: **RICHARD FRANCIS FREITAS**, SAN MARTIN, CA (US); **DIVYESH JADAV**, CAMPBELL, CA (US); **DEEPAK KENCHAMMANA-HOSEKOTE**, SUNNYVALE, CA (US); **JAISHANKAR MOOTHEDATH MENON**, SAN JOSE, CA (US); **HOVEY RAYMOND STRONG JR.**, SAN JOSE, CA (US)

Correspondence Address:
Dan Hubert & Associates
3111 Camino Del Rio North
4th floor
San Diego, CA 92108 (US)

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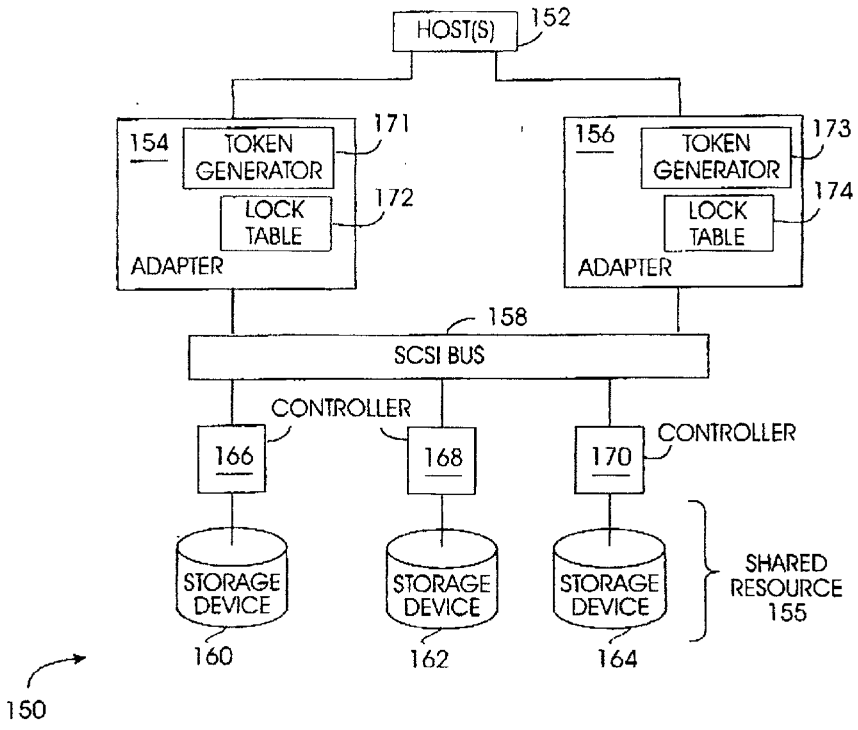
(57) **ABSTRACT**

Multiple competing processors cooperatively manage access to a shared resource. Each processor separately stores a lock table, listing shared resource subparts, such as memory addresses of a data storage device, for example. The lock tables are stored in nonvolatile storage. In each lock table, each subpart is associated with a "state," such as LOCAL or REMOTE. In response to access requests from the hosts, the processors exchange various messages to cooperatively elect a single processor to have exclusive access to the subparts involved in the access requests. After one processor is elected, the lock-holding processor configures its lock table to show the identified subpart in the LOCAL state, and all non-lock-holding processors configure their lock tables to show the identified subpart in the REMOTE state. Thus, rather than replicating one lock table for all processors, the processors separately maintain lock tables that are coordinated with each other. Importantly, each processor honors its lock table by refraining from accessing a subpart of the shared resource unless the processor's lock table indicates a LOCAL state for that subpart. In one embodiment, optimized for the two processor environment, the messages exchanged by the processors include lock request, lock release, and lock grant messages.



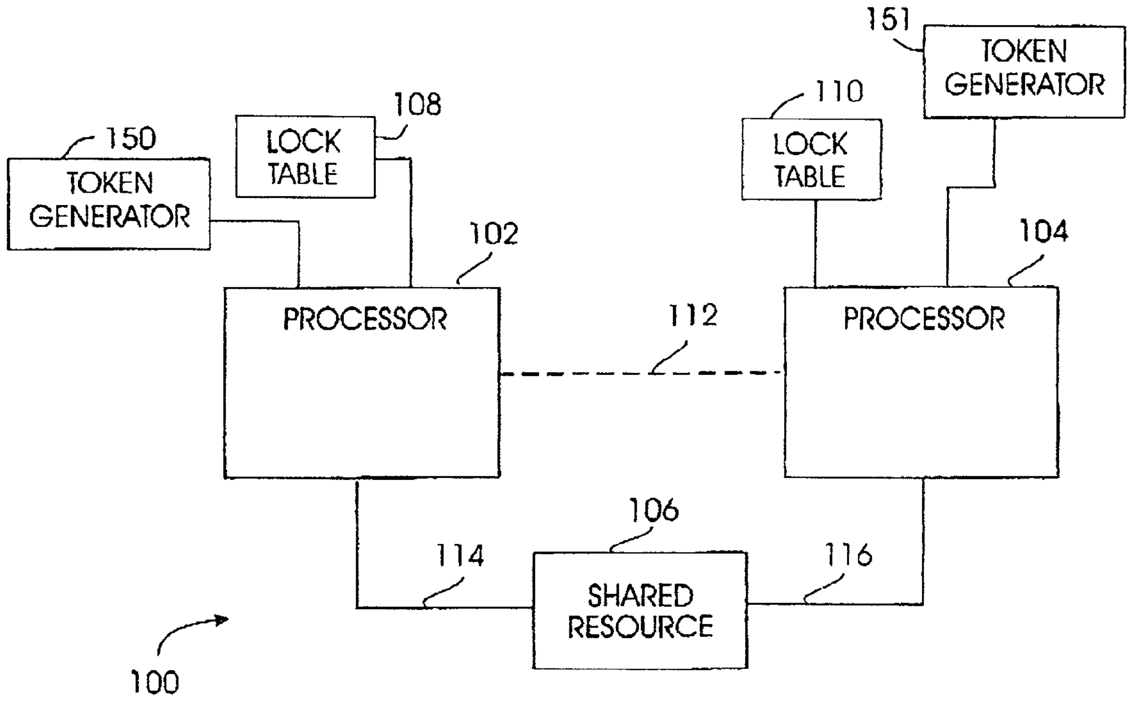

151
TOKEN GENERATOR
108
110
150
LOCK TABLE
LOCK TABLE
TOKEN GENERATOR
102
104
PROCESSOR
112
PROCESSOR
106
114
116
SHARED RESOURCE
100

FIG. 1A

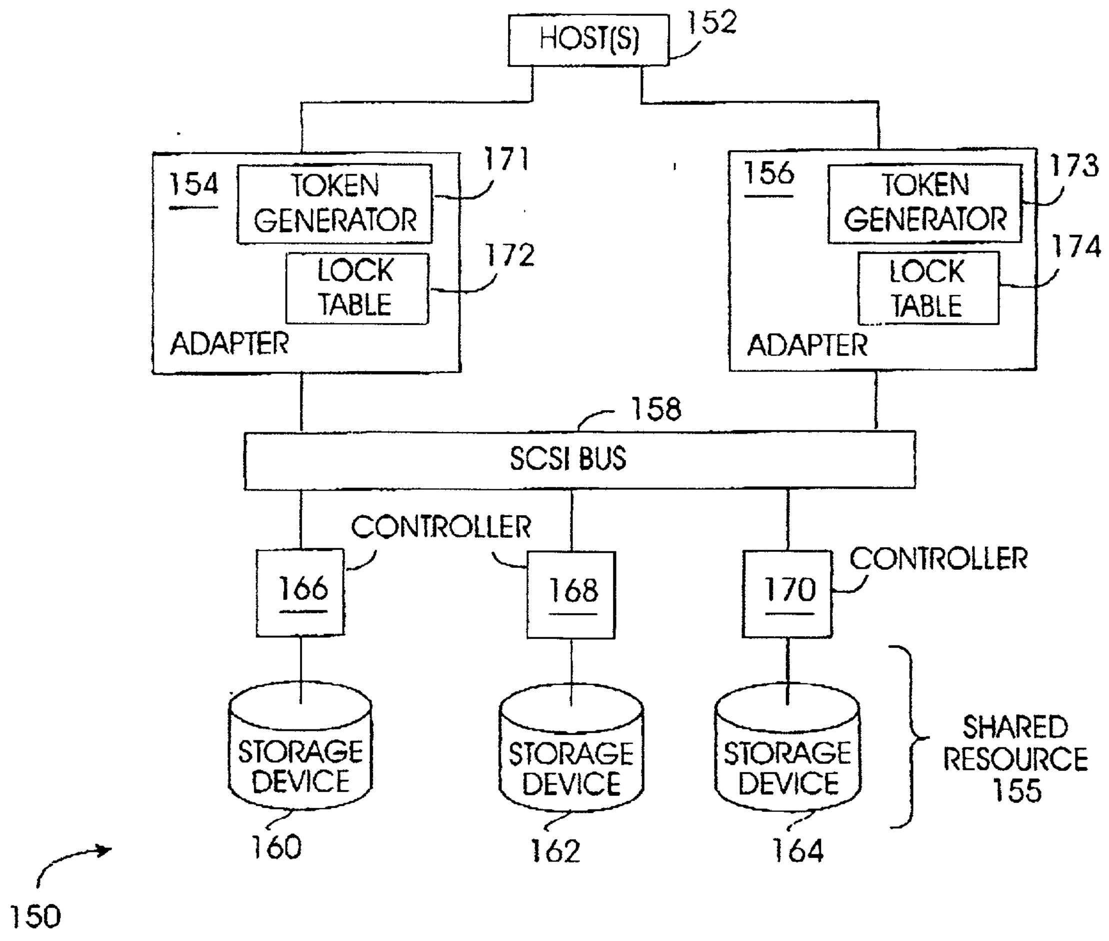

HOST(S)
152
154
TOKEN GENERATOR
171
LOCK TABLE
172
ADAPTER
156
TOKEN GENERATOR
173
LOCK TABLE
174
ADAPTER
158
SCSI BUS
CONTROLLER
166
168
170
CONTROLLER
STORAGE DEVICE
160
STORAGE DEVICE
162
STORAGE DEVICE
164
SHARED RESOURCE 155
150

FIG. 1B

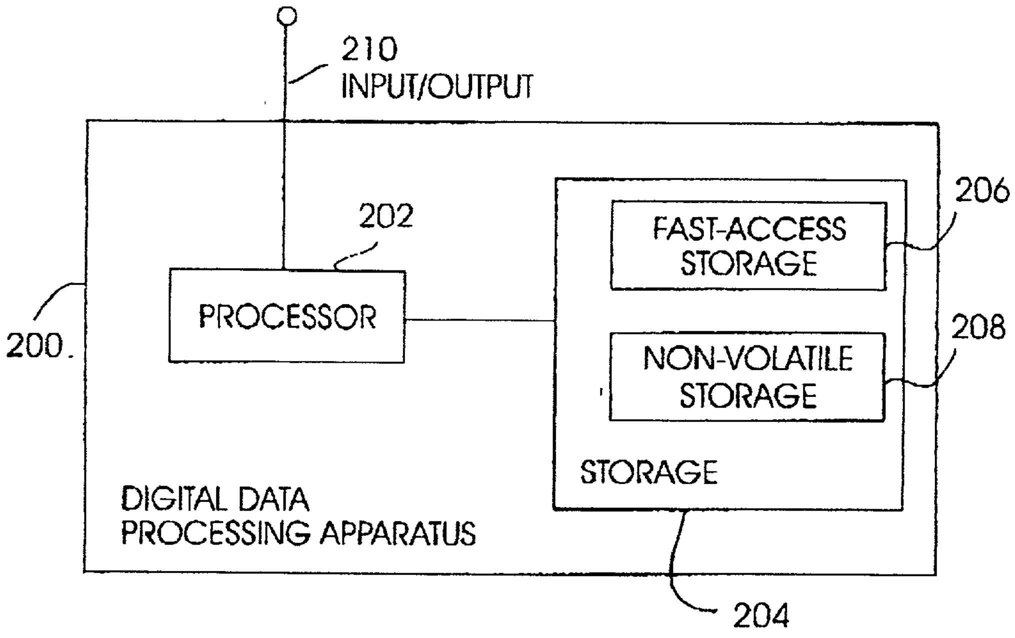

210
INPUT/OUTPUT
202
PROCESSOR
206
FAST-ACCESS STORAGE
208
NON-VOLATILE STORAGE
STORAGE
200
DIGITAL DATA PROCESSING APPARATUS
204

FIG. 2

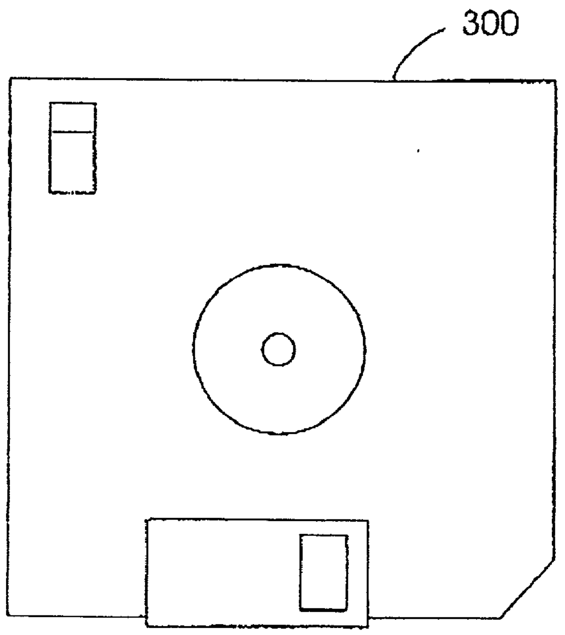
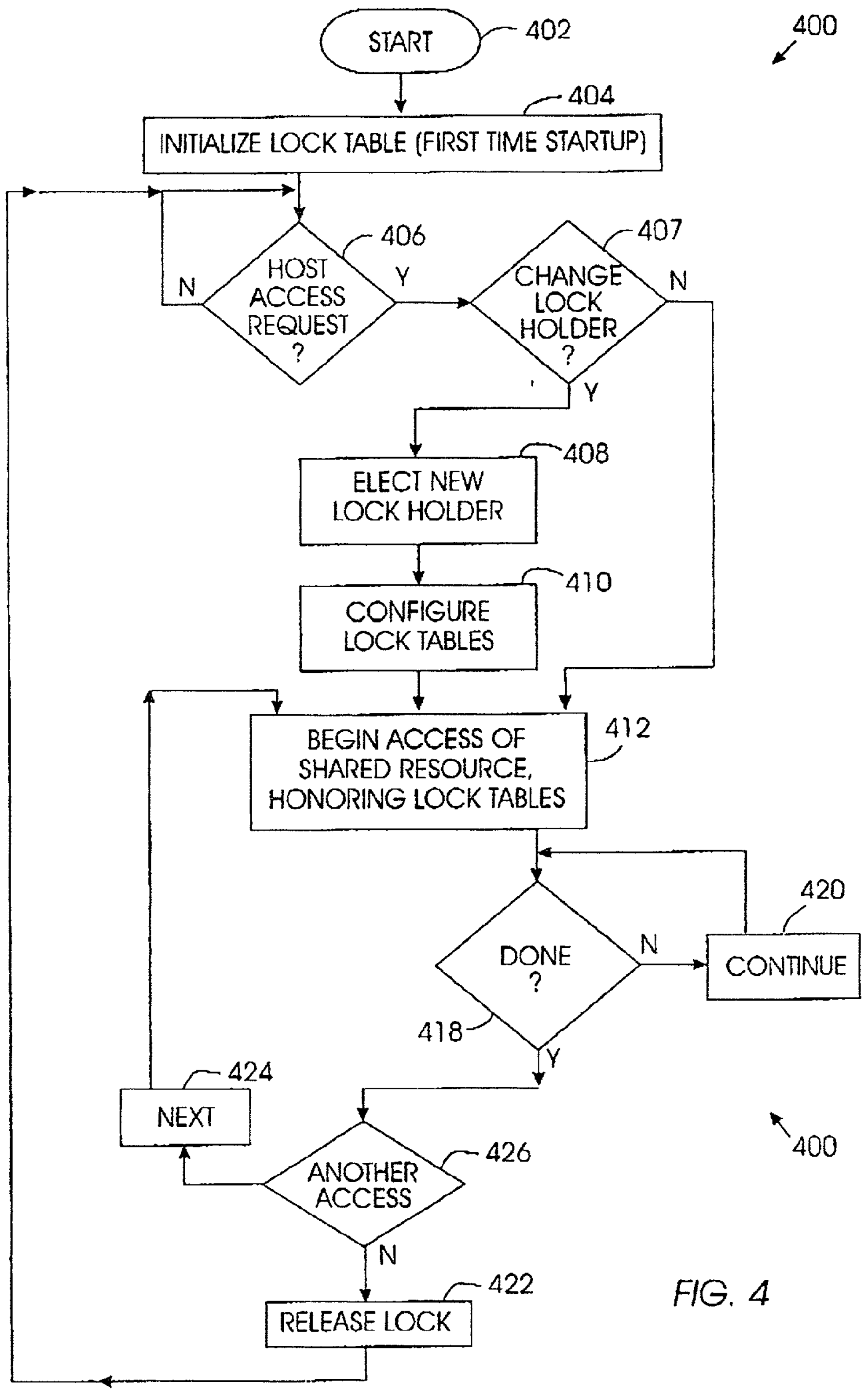

300

FIG. 3



400
START
402
INITIALIZE LOCK TABLE (FIRST TIME STARTUP)
404
HOST ACCESS REQUEST ?
406
N
Y
CHANGE LOCK HOLDER ?
407
N
Y
ELECT NEW LOCK HOLDER
408
CONFIGURE LOCK TABLES
410
BEGIN ACCESS OF SHARED RESOURCE, HONORING LOCK TABLES
412
DONE ?
418
N
CONTINUE
420
Y
NEXT
424
ANOTHER ACCESS
426
N
RELEASE LOCK
422
400

FIG. 4

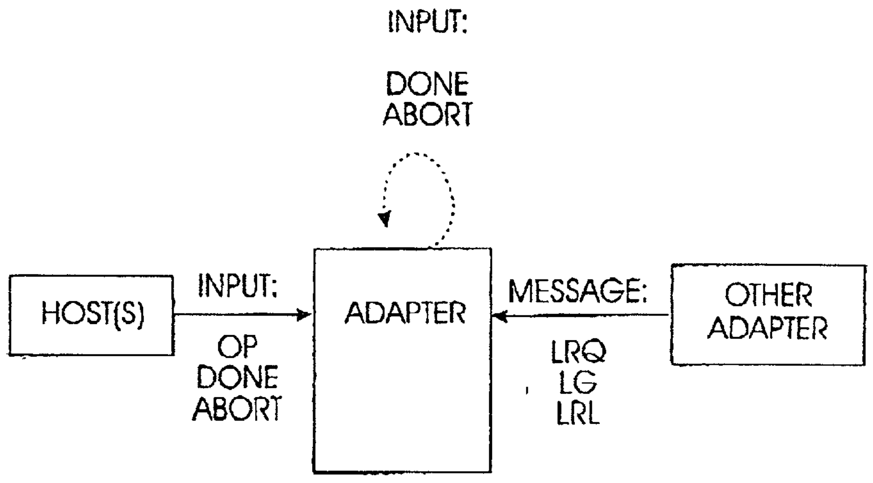

INPUT:
DONE
ABORT
HOST(S)
INPUT:
OP
DONE
ABORT
ADAPTER
MESSAGE:
LRQ
LG
LRL
OTHER ADAPTER

FIG. 4A

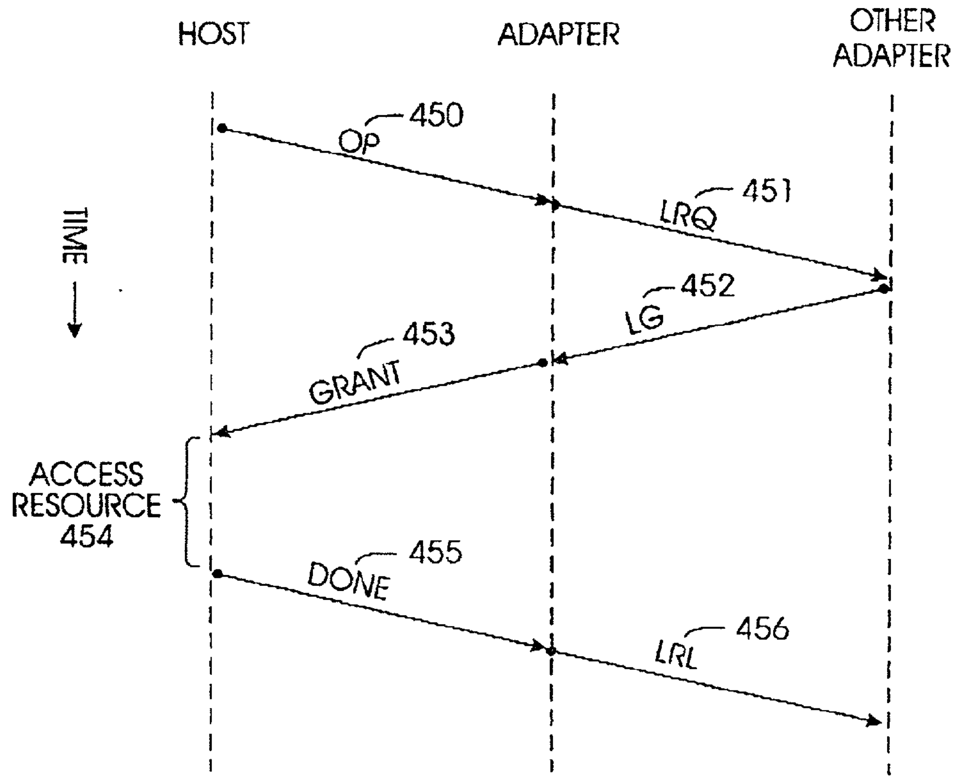

HOST
ADAPTER
OTHER ADAPTER
TIME
OP
450
LRQ
451
LG
452
GRANT
453
ACCESS RESOURCE 454
DONE
455
LRL
456

FIG. 4B

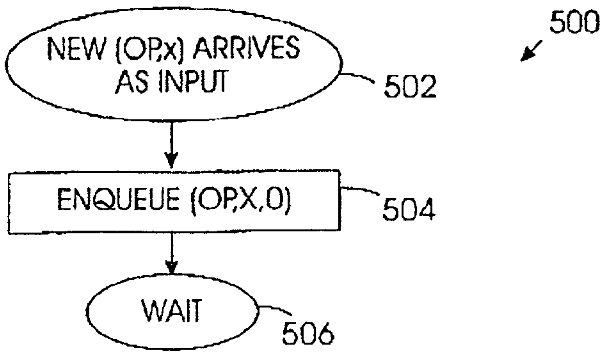

500
NEW (OP,x) ARRIVES AS INPUT
502
ENQUEUE (OP,X,0)
504
WAIT
506

FIG. 5

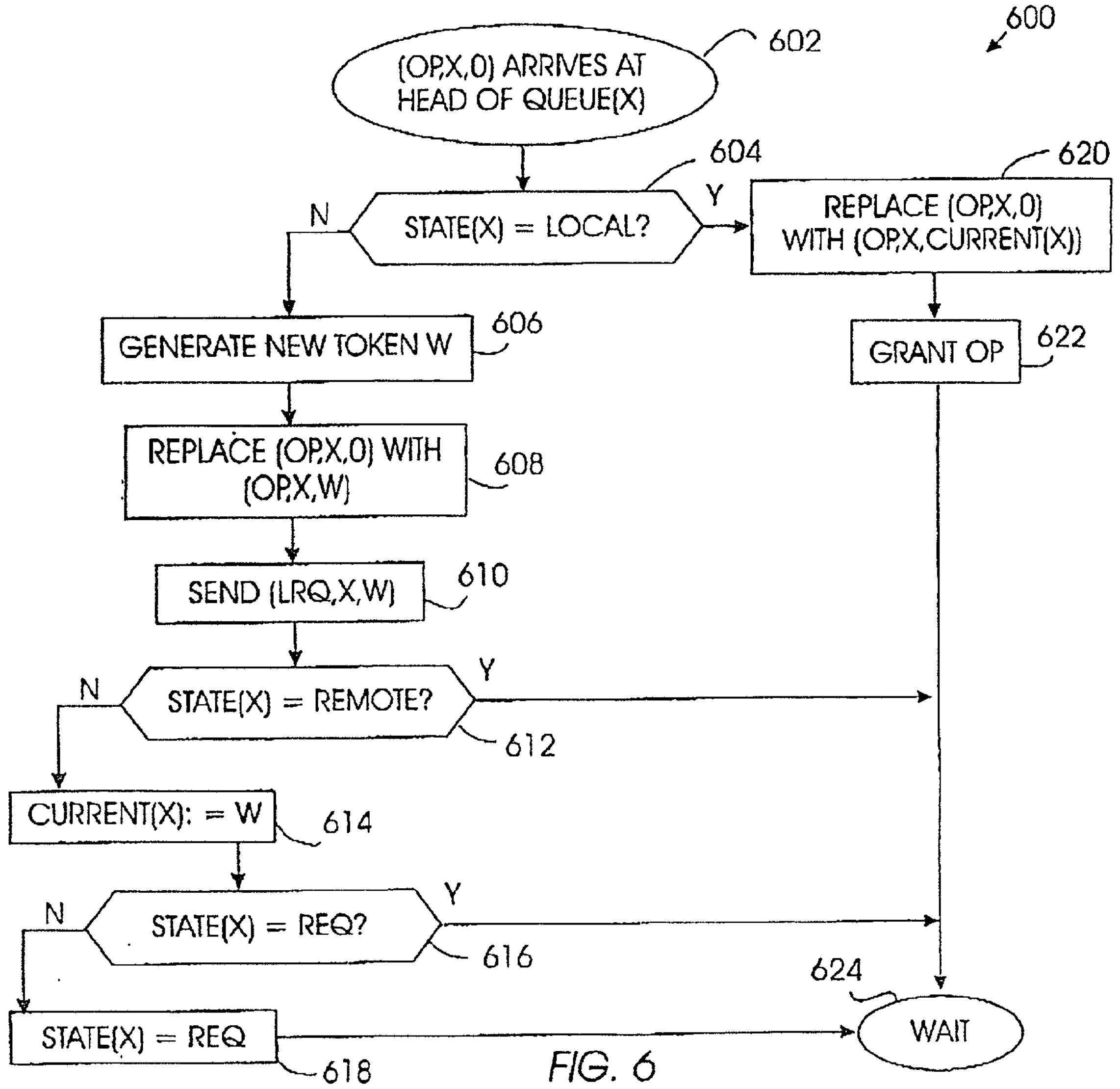

600
(OP,X,0) ARRIVES AT HEAD OF QUEUE(X)
602
604
STATE(X) = LOCAL?
N
Y
REPLACE (OP,X,0) WITH (OP,X,CURRENT(X))
620
GENERATE NEW TOKEN W
606
GRANT OP
622
REPLACE (OP,X,0) WITH (OP,X,W)
608
SEND (LRQ,X,W)
610
STATE(X) = REMOTE?
N
Y
612
CURRENT(X): = W
614
STATE(X) = REQ?
N
Y
616
624
STATE(X) = REQ
618
WAIT

FIG. 6

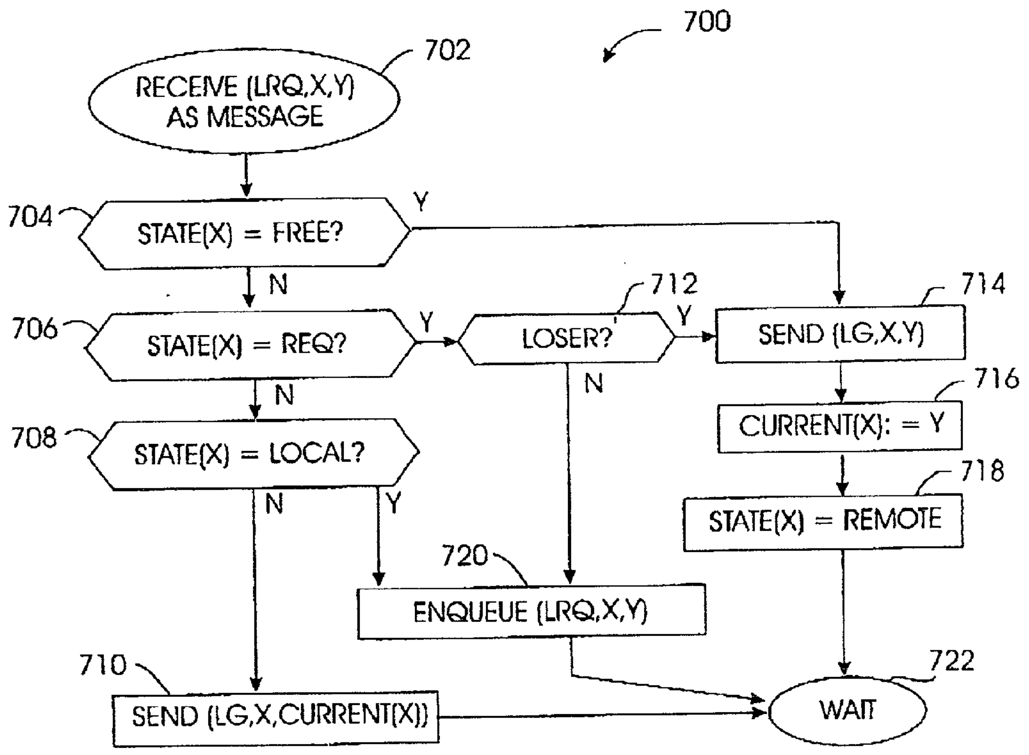

700
702
RECEIVE (LRQ,X,Y) AS MESSAGE
704
STATE(X) = FREE?
Y
N
706
STATE(X) = REQ?
Y
712
LOSER?
Y
N
714
SEND (LG,X,Y)
716
CURRENT(X): = Y
718
STATE(X) = REMOTE
N
708
STATE(X) = LOCAL?
N
Y
720
ENQUEUE (LRQ,X,Y)
710
SEND (LG,X,CURRENT(X))
722
WAIT

FIG. 7

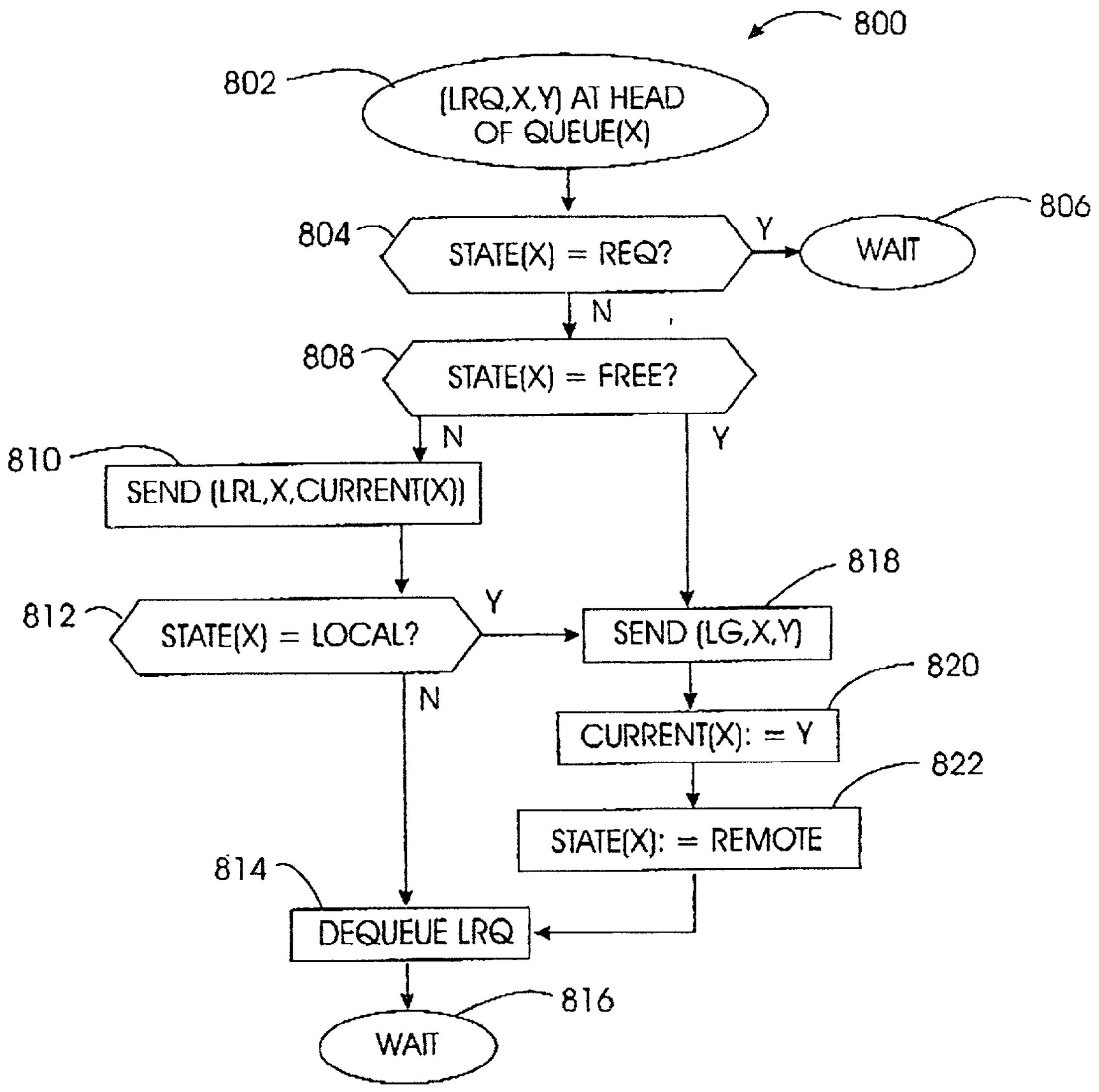

800
802
(LRQ,X,Y) AT HEAD OF QUEUE(X)
804
STATE(X) = REQ?
Y
806
WAIT
N
808
STATE(X) = FREE?
N
Y
810
SEND (LRL,X,CURRENT(X))
812
STATE(X) = LOCAL?
Y
N
818
SEND (LG,X,Y)
820
CURRENT(X): = Y
822
STATE(X): = REMOTE
814
DEQUEUE LRQ
816
WAIT

FIG. 8

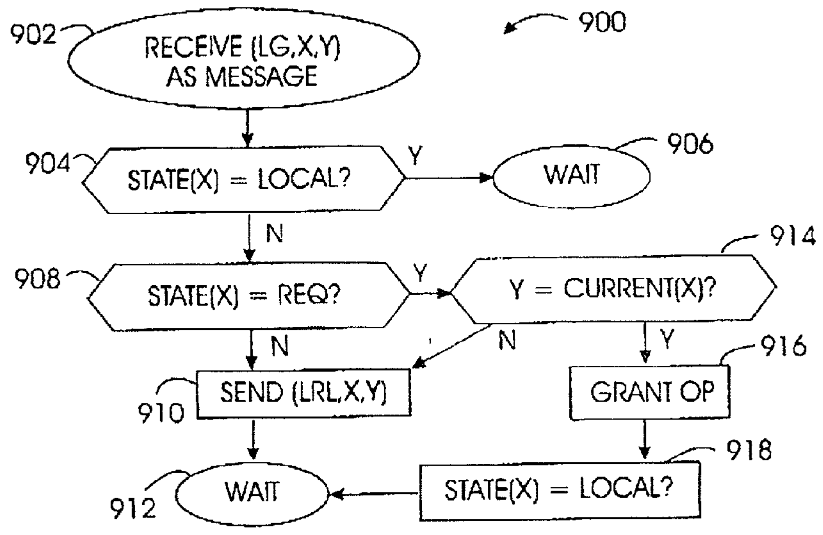

900
902
RECEIVE (LG,X,Y) AS MESSAGE
904
STATE(X) = LOCAL?
Y
WAIT
906
N
908
STATE(X) = REQ?
Y
Y = CURRENT(X)?
914
N
N
Y
SEND (LRL,X,Y)
910
GRANT OP
916
WAIT
912
STATE(X) = LOCAL?
918

FIG. 9

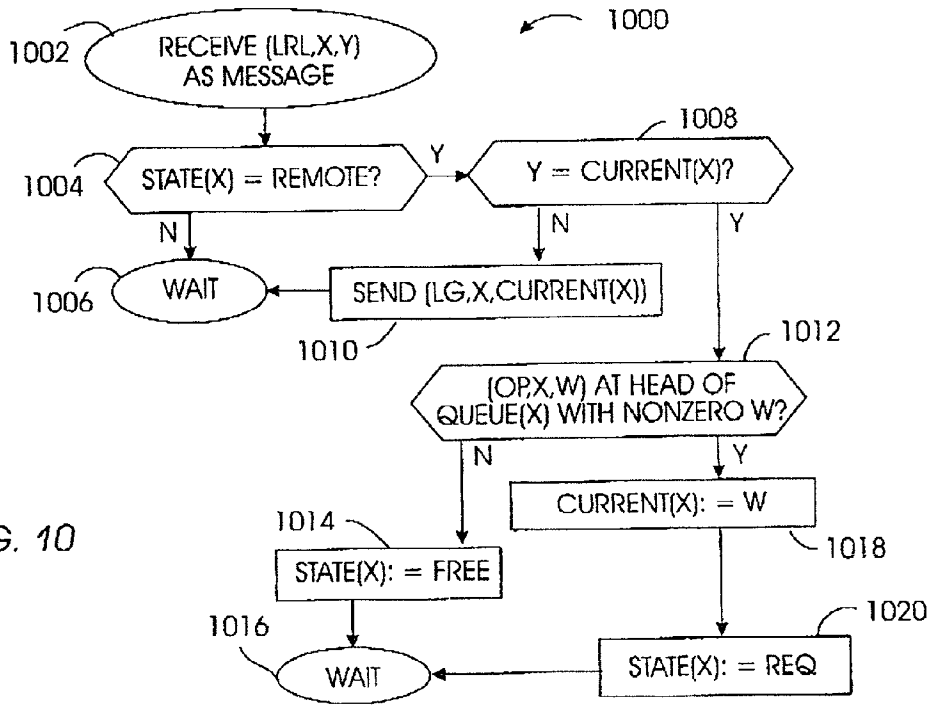

1000
1002
RECEIVE (LRL,X,Y) AS MESSAGE
1004
STATE(X) = REMOTE?
Y
Y = CURRENT(X)?
1008
N
WAIT
1006
N
SEND (LG,X,CURRENT(X))
1010
Y
1012
(OP,X,W) AT HEAD OF QUEUE(X) WITH NONZERO W?
N
Y
CURRENT(X): = W
1018
1014
STATE(X): = FREE
1016
WAIT
STATE(X): = REQ
1020

FIG. 10

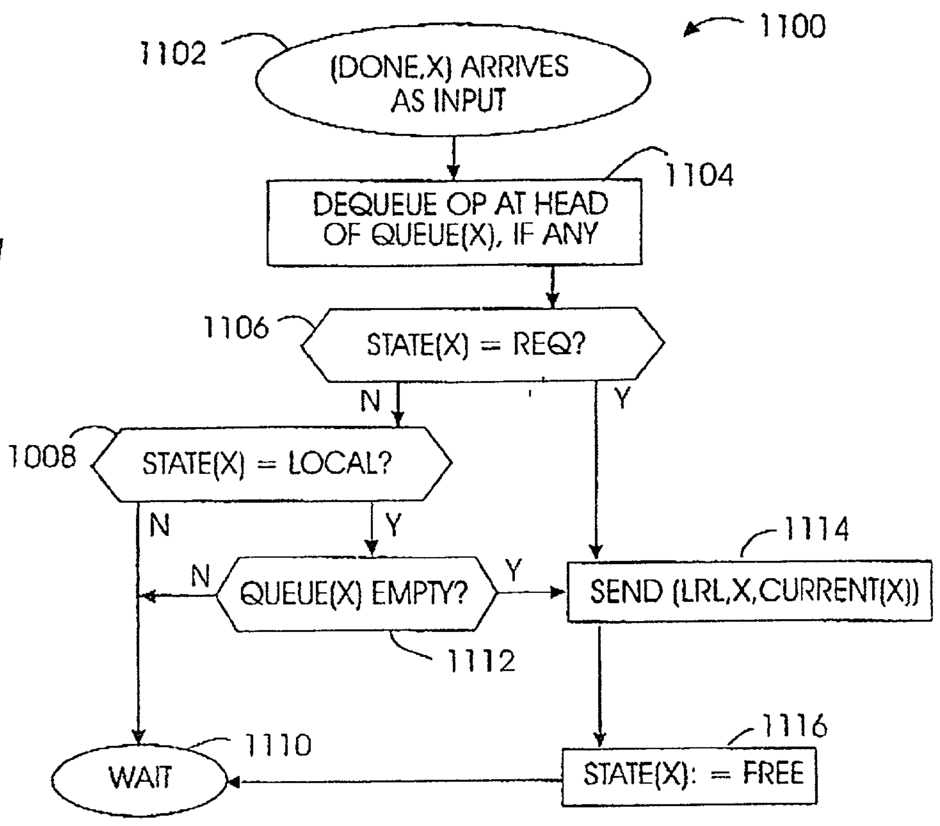

1100
1102
(DONE,X) ARRIVES AS INPUT
1104
DEQUEUE OP AT HEAD OF QUEUE(X), IF ANY
1106
STATE(X) = REQ?
N
Y
1008
STATE(X) = LOCAL?
N
Y
N
QUEUE(X) EMPTY?
Y
1112
1114
SEND (LRL,X,CURRENT(X))
1110
WAIT
1116
STATE(X): = FREE

FIG. 11

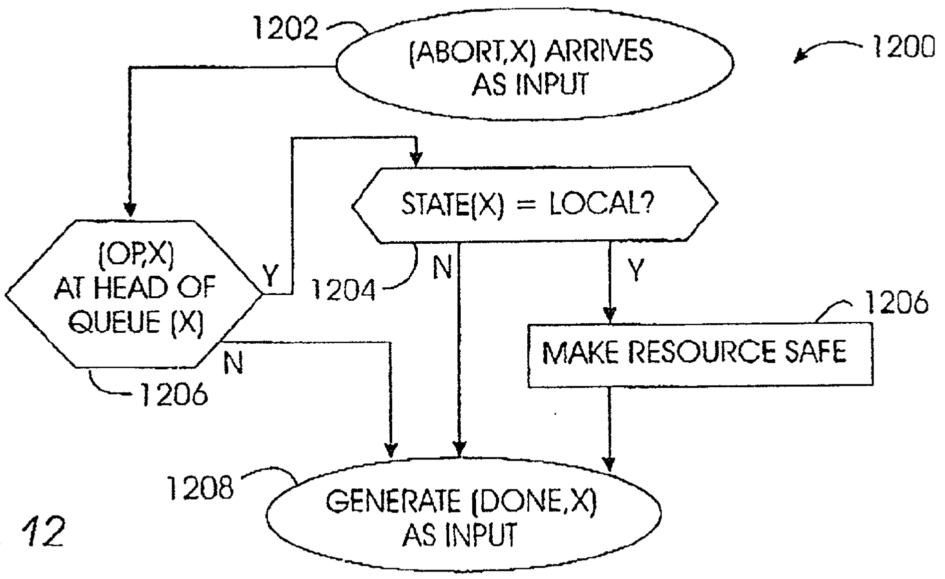

1202
(ABORT,X) ARRIVES AS INPUT
1200
STATE(X) = LOCAL?
(OP,X) AT HEAD OF QUEUE (X)
Y
1204
N
Y
1206
MAKE RESOURCE SAFE
N
1206
1208
GENERATE (DONE,X) AS INPUT

FIG. 12

METHOD FOR MANAGING CONCURRENT PROCESSES USING DUAL LOCKING

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to computer systems with multiple processing units. More particularly, the invention concerns a method for managing access to a shared resource among competing processing units.

[0003] 2. Description of the Related Art

[0004] Today people are confronted with an astonishing amount of electronic information to manage. Such management involves transmitting, receiving, processing, and storing electronic data. To meet these challenges, many people choose to computer systems with multiple processing units. These systems enjoy significant computing power by using separate computers, microprocessors, processing threads, or other types of processing. These processing units may also be known by terms such as processors, processing elements, etc.

[0005] One recurring challenge to systems with multiple processors involves the sharing of resources by the multiple processors. As one example, digital data storage such as magnetic "hard" disk drive storage is often shared by multiple storage "adapters." Sharing such a resource is challenging because of the difficulties in arbitrating access to the resource. At any given time, which processor should be permitted access to the shared resource? Should other processors be given limited concurrent access? This is further complicated by the need to plan for possible failure of a processor or communications between the processors.

[0006] One popular approach to sharing computer resources is called "mutual exclusion," which is often applied at the device level. With this approach, processors access the resource one-at-a-time. While one processor is accessing the resource, all other processors are excluded from that device. Although this approach is attractive in its simplicity, shared computer resources often possess significantly more input/output ("I/O") capability than the processors that manage them. In this case, the full throughput of the shared resource is wasted when it is being used by one processor to the exclusion of the other processors.

[0007] In the case of storage resources, the system takes longer to store and retrieve data when the processors are confined by one-at-a-time access rules. This is undesirable, since slower data storage and retrieval are frustrating to most computer users. Furthermore, slow data access maybe intolerable in certain data-critical applications, such as automated teller networks, airline reservation systems, stock brokerage, etc. Furthermore, the use of mutual exclusion is complicated by the possibility that a processor with exclusive access to the shared resource experiences a failure, causing a severe problem for the excluded processors.

[0008] To orchestrate mutual exclusion, competing processors must exchange messages of some type. A different set of problems is thus presented by the possibility that messages are lost while a device is reserved to one processor, causing a situation known as "livelock." A further difficulty inherent to mutual exclusion schemes is the need to fairly allocate access to the shared resource among competing processors, the consequences of misallocation potentially including "starvation" of the losing processor.

[0009] Consequently, known strategies for arbitrating processor access to shared resources are not completely adequate for some applications due to various unsolved problems.

SUMMARY OF THE INVENTION

[0010] Broadly, the present invention concerns a method and apparatus for managing access to a shared resource among competing processors. The invention includes features that are particularly optimized for environments with two "processors," also referred to as processing units, processing elements, nodes, servers, computers, adapters, etc. The invention is applied in a system with multiple processors that commonly access a shared resource, such as a digital data storage. The processors receive and process access requests originating at one or more hosts.

[0011] Each processor separately stores a lock table, listing subparts of the shared resource, such as memory addresses, extents, logical devices, or an entire physical data storage device. The lock tables are stored in nonvolatile storage. In each lock table, each subpart of the shared resource is associated with a "state" such as LOCAL or REMOTE. In response to access requests from the hosts, the processors exchange various messages to cooperatively elect a single processor to have exclusive access to the subparts involved in the access requests. After one processor is elected, the lock-holding processor configures its lock table to show the identified subpart in the LOCAL state, and all non-lock-holding processors configure their lock tables to show the identified subpart in the REMOTE state. Thus, rather than replicating one lock table for all processors, the processors separately maintain lock tables that are coordinated with each other. Importantly, each processor refrains from accessing a subpart of the shared resource unless the processor's lock table indicates a LOCAL state for that subpart.

[0012] In one embodiment, optimized for the two processor environment, the messages exchanged by the processors include lock request, lock release, and lock grant messages. When a processor seeks access to a subpart, but its lock table indicates a REMOTE state for the lock, the other processor owns the lock. In this case, the first processor transmits a lock request to the other processor. The lock-holding processor enqueues the lock request. The lock-holding processor sequentially processes queued messages, and upon reaching the first processor's lock request, the second processor takes steps to hand the lock to the first processor. In particular, the second processor configures its lock table to indicate the REMOTE state for the subpart, and then transmits a lock grant message back to the first processor. In response, the first processor configures its lock table to show the subpart in the LOCAL state, at which point the first processor is free to access the requested shared resource subpart.

[0013] To increase reliability of message exchange, each message may include a token, where the processors require matching tokens for corresponding messages, such as lock grant and lock release messages. Using tokens increases the system's tolerance of lost messages, duplicated messages, misordered messages, communication faults, etc.

[**0014**] The subpart states may also include a FREE state, in which no processor holds a lock on that subpart. In this case, a requesting processor's lock request message can be satisfied with a prompt lock grant from the other processor.

[**0015**] Accordingly, in one embodiment the invention may be implemented to provide a method to manage access to a shared resource among competing processors. In another embodiment, the invention may be implemented to provide an apparatus, such as an adapter or other processing unit of a system with multiple processors, programmed to participate in the management of shared resource access. In still another embodiment, the invention may be implemented to provide a signal-bearing medium tangibly embodying a program of machine-readable instructions executable by a digital data processing apparatus to perform method steps for managing access to a shared resource among competing processors.

[**0016**] The invention affords its users with a number of distinct advantages. First, the invention takes advantage of the high-throughput capability of shared resources by more efficiently sharing the resources. In the data storage environment, for example, the invention stores and retrieves data more quickly. Consequently, computer users are more pleased with their systems, since they are faster to use. The invention is especially beneficial for the common configuration where two adapters or other processors share access to a common resource.

[**0017**] Furthermore, the invention provides a number of desirable properties for a dual locking protocol. These include safety, liveness, fairness, and efficiency. Safety is provided because if a lock is in the LOCAL state at one adapter, then it is in the REMOTE state at the other adapter. Liveness is provided because the invention guarantees eventual progress in granting locks, since individual locks are eventually released (because of completion or timeout), and because frustrated processors make repeated requests for a lock. Fairness is provided because each processor makes eventual progress in obtaining a lock without "starving" the other adapter. Efficiency is provided because there is minimal overhead involved in maintaining the status quo when a lock-holding processor receives multiple local requests for a lock while the other processor receives none.

[**0018**] The invention also provides a number of other advantages and benefits, which should be apparent from the following description of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[**0019**] **FIG. 1A** is a block diagram of the hardware components and interconnections of a system with multiple processors in accordance with the invention.

[**0020**] **FIG. 1B** is a block diagram of a digital data storage system employing dual locking in accordance with the invention.

[**0021**] **FIG. 2** is a block diagram of a digital data processing machine in accordance with the invention.

[**0022**] **FIG. 3** shows an exemplary signal-bearing medium in accordance with the invention.

[**0023**] **FIG. 4** is a flowchart depicting an overall operational sequence for accessing a shared resource using dual locking in accordance with the invention.

[**0024**] **FIG. 4A** is a partial system diagram showing the movement and source of one adapter's messages and input in a two adapter arrangement, in accordance with the invention.

[**0025**] **FIG. 4B** is a time-based event diagram illustrating an exemplary exchange of signals during the process of acquiring a lock, in accordance with the invention.

[**0026**] **FIG. 5** is a flowchart depicting a sequence performed by a processor when a new local request for a lock (OP) arrives, in accordance with the invention.

[**0027**] **FIG. 6** is a flowchart depicting a sequence performed by a processor when a queued local request for a lock (OP) arrives at the head of the queue, in accordance with the invention.

[**0028**] **FIG. 7** is a flowchart depicting a sequence performed by a processor when a lock request (LRQ) message arrives, in accordance with the invention.

[**0029**] **FIG. 8** is a flowchart depicting a sequence performed by a processor when an enqueued lock request (LRQ) arrives at the head of the queue, in accordance with the invention.

[**0030**] **FIG. 9** is a flowchart depicting an sequence performed by a processor when a lock grant (LG) message arrives, in accordance with the invention.

[**0031**] **FIG. 10** is a flowchart depicting an sequence performed by a processor when a lock release (LRL) message arrives, in accordance with the invention.

[**0032**] **FIG. 11** is a flowchart depicting an sequence performed by a processor when a completion input (DONE) arrives, in accordance with the invention.

[**0033**] **FIG. 12** is a flowchart depicting an sequence performed by a processor when an error input (ABORT) arrives, in accordance with the invention.

DETAILED DESCRIPTION

[**0034**] The nature, objectives, and advantages of the invention will become more apparent to those skilled in the art after considering the following detailed description in connection with the accompanying drawings. As mentioned above, the invention concerns the management of access to a shared resource among competing processors.

Hardware Components & Interconnections

Multiple-Processor System

[**0035**] One aspect of the invention concerns a system with multiple processors, which may be embodied by various hardware components and interconnections as shown by the system **100** of **FIG. 1A**. The system **100** includes two processors **102**, **104** and a shared resource **106**. The processors **102**, **104** may be provided by hardware constructs (e.g., microprocessors, supercomputers, mainframe computers, computer workstations, personal computers, or other suitable digital data processing machines), software (e.g., processes, processing threads, software programs, subroutines, firmware, etc.), or a combination of hardware and software.

[**0036**] The shared resource **106** may comprise any machine with storage, computing power, or other machine-accessible resource that is subdivisible into different subcomponents. As shown below, one example is a digital data storage, subdivisible into different storage addresses, ranges of addresses, address extents, logical devices, physical devices, etc.

[**0037**] The processors **102**, **104** exchange machine-readable messages with the shared resource **106** over respective communications links **114**,**116**. Inter-processor communication occurs over a communication link **112**. The links **112**, **114**, **116** may be embodied by one or more cables, wires, backplanes, motherboards, fiber optic lines, infrared links, telephone line, intelligent communications channel, electromagnetic or other wireless links, computer networks (such as Internet, Intranet, wide area, LOCAL area, etc.), or another suitable mechanism for exchanging machine-readable messages. Furthermore, the link **112** maybe eliminated completely with the links **114**, **116** being interconnected to provide a link between the two processors **102**, **104**. As another approach, the links **114**, **116** may be eliminated with the resource **106** coupled to the link **112**. Ordinarily skilled artisan (having the benefit of this disclosure) may recognize of variety of other approaches as well.

[**0038**] Each processor **102**, **104** exclusively maintains a respective lock table **108**, **110**. The lock tables **108**, **110** are contained in storage accessible by the processors **102**, **104**, which may be provided by nonvolatile storage device such as battery backed RAM memories, magnetic disk drives, optical tape, optical disk, magnetic tape, paper punch cards, or another suitable machine-accessible storage. As explained further below, each processor maintains in association with its lock table a queue of shared resource requests that are awaiting execution by the lock table's processor. For each subpart of the shared resource, the processors **102**, **104** exchange certain messages to decide which processor will have exclusive access to that subpart.

[**0039**] Each processor **102**, **104** also includes or otherwise has exclusive access to a respective token generator **150**, **151**. The token generators **150**, **151** operate **20** independently of each other. Each token generator **150**, **151** comprises a mechanism to generate a code, which is used to increase the system's tolerance of lost messages. As discussed below, each message exchanged between the processors **102**, **104** includes a token. New messages include a new token of the originating processor, whereas messages responding to another message must carry that earlier message's token to associate the two messages and thereby be effective.

[**0040**] In the present example, the token generators provide tokens that are binary numbers. Thus, the token generators **150**, **151** may compromise respective registers, memory addresses, counters, etc. A token is generated in this example by incrementing a token generator. Each of the token generators **150**, **151** provides a new token after one of its tokens is used or "grabbed." For instance, if the processor **102** obtains ("grabs") a token from the generator **151**, the generator **151** then proceeds to generate a new token.

[**0041**] In the illustrated example, tokens of the token generators **150**, **151** are non overlapping. In other words, each generator's tokens never match any tokens provided by the other generator. Where binary number tokens are used, this feature may be provided by ensuring that one token generator's most significant bit is always zero, whereas the other token generator's most significant bit is always one.

[**0042**] Additionally, each token generator is configured to rarely, if ever, repeat the same token. As an example, this feature may be provided by using a binary generator with a sufficiently high number of bits (e.g., thirty-two bits). A repeat cycle of about one year may be used successfully in many cases.

EXAMPLE

Storage System

[**0043**] **FIG. 1B** depicts a more particular example of the multiple processor system of the invention, in the form of a digital data storage system **150**, in which the shared resource comprises data storage. The system **150** includes two storage adapters **154**,**156** and a shared resource **155**. The adapters **154**, **156** are coupled to one or more hosts **152**. The adapters **154**, **156** may be coupled to the same host(s), completely different hosts, or a mix of common and distinct hosts. In one example, the adapters **154**, **156** may comprise printed circuit boards physically and electrically mounted within the host(s) **152**. As an even more specific example, the adapters **154**, **156** may comprise IBM model ServeRAID II adapters.

[**0044**] In this example, each adapter **154**, **156** houses a respective lock table **172**, **174**, stored in nonvolatile storage aboard the adapter. The nonvolatile storage may comprise, for example, random access memory ("RAM") with backup battery power, optical storage, hard drive storage, etc. The lock tables may comprise tables, linked lists, ASCII text, or another data structure suitable for storing information of the type discussed below.

[**0045**] Each adapter also includes a respective token generator **171**, **173**. The structure and operation of the token generators **171**, **173** may resemble the token generators **150**, **151**, discussed above.

[**0046**] The shared resource **155** comprises some or all of one or more digital data storage devices. Such devices may include magnetic disk drives, optical tape, optical disk, magnetic tape, paper punch cards, or another suitable machine-accessible storage. A specific example is an IBM brand RAMAC disk drive storage subsystem. The shared resource **155** is subdivisible into "subparts," such as physical devices, logical devices, addresses, address ranges, extents, cylinders, sectors, or another unit. In the present example, the shared resource **155** is illustrated by multiple storage devices **160**, **162**, **164**, managed by respective device controllers **166**, **168**, **170**.

[**0047**] A common bus **158** is coupled to the controllers **166**, **168**, **170** and the adapters **154**, **156** alike. In this example, the bus **158** comprises a small computer standard interface ("SCSI") bus, and carries communications between the adapters and the storage controllers, as well as between the adapters.

Exemplary Digital Data Processing Apparatus

[**0048**] Another aspect of the invention concerns a digital data processing apparatus, constituting one of the competing processors, or a component thereof, seeking access to a resource shared with another processor. This apparatus may be embodied by various hardware components and interconnections, and may be implemented in one example to provide the adapters **154**, **156** (**FIG. 1B**).

[0049] **FIG. 2** shows an example of one digital data processing apparatus **200**. The apparatus **200** includes a processor **202**, such as a microprocessor or other processing machine, coupled to a storage **204**. In the present example, the storage **204** includes a fast-access storage **206**, as well as nonvolatile storage **208**. The fast-access storage **206** may comprise RAM, and may be used to store the programming instructions executed by the processor **202**. The nonvolatile storage **208** may comprise, for example, one or more magnetic data storage disks such as a "hard drive," a tape drive, or any other suitable storage device. The apparatus **200** also includes an input/output **210**, such as a line, bus, cable, electromagnetic link, or other means for exchanging data with the processor **202**.

[0050] Despite the specific foregoing description, ordinarily skilled artisans (having the benefit of this disclosure) will recognize that the apparatus discussed above may be implemented in a machine of different construction, without departing from the scope of the invention. As a specific example, one of the components **206**, **208** may be eliminated; furthermore, the storage **204** may be provided onboard the processor **202**, or even provided externally to the apparatus **200**.

Operation

[0051] In addition to the various hardware embodiments described above, a different aspect of the invention concerns a method for managing access to a shared resource among multiple competing processors.

Signal-Bearing Media

[0052] In the context of **FIGS. 1B and 2**, for example, such a method may be implemented, for example, by operating the adapters **154**, **156**, each as embodied by a digital data processing apparatus **200**, to execute a sequence of machine-readable instructions. These instructions may reside in various types of signal-bearing media. In this respect, one aspect of the present invention concerns a programmed product, comprising signal-bearing media tangibly embodying a program of machine-readable instructions executable by a digital data processor to enable the processor to manage access to a shared resource relation to a competing processor.

[0053] This signal-bearing media may comprise, for example, RAM (not shown) contained within the adapter **154**, **156** (**FIG. 1B**), as represented by the fast-access storage **206** (**FIG. 2**). Alternatively, the instructions may be contained in another signal-bearing media, such as a magnetic data storage diskette **300** (**FIG. 3**), directly or indirectly accessible by the adapter **154**, **156**. Whether contained in the adapters **154**, **156** or elsewhere, the instructions may be stored on a variety of machine-readable data storage media, such as direct access storage (e.g., a conventional "hard drive" or a RAID array), magnetic tape, electronic read-only memory (e.g., ROM, EPROM, or EEPROM), an optical storage device (e.g., CD-ROM, WORM, DVD, digital optical tape), paper "punch" cards, or other suitable signal-bearing media including transmission media such as digital and analog and communication links and wireless. In an illustrative embodiment of the invention, the machine-readable instructions may comprise software object code, compiled from a language such as "C," etc.

Overall Sequence of Operation

[0054] **FIG. 4** shows a sequence **400** to provide an overall description of the method aspect of the present invention. For ease of explanation, but without any intended limitation, the example of **FIG. 4** is described in the context of the hardware environment of **FIG. 1B**, described above. The sequence **400** begins in step **402**, which may be performed whenever the system **150** is powered up, rebooted, or otherwise initiated.

[0055] In step **404**, the adapters **154**, **156** initialize their respective lock tables **172**, **174** if needed. Namely, initialization is necessary of this is a first time startup, where no previous lock tables exist. In one embodiment, this may involve allocating storage for the lock tables **172**, **174**, preparing pointers, and performing other storage tasks to ready the tables for use. If desired, step **404** may additionally prepare blank entries in the lock table, where each entry corresponds to the minimum size of separately accessible shared resource subpart, such as a single address, partition, etc.

[0056] After step **404**, the adapters **154**, **156** await shared resource access requests from the hosts **152** (step **406**). In response to such a request, which involves one or more identified subparts, the adapters **154**, **156** cooperatively determine whether there should be any change in the lock holder (step **407**). For instance, if no adapter holds the lock on the requested subparts, a change in the lock holder is needed to give the lock to the adapter that received the access request. In another example, the processor already owning the lock may maintain a queue of lock requesting tasks, including its own and lock requests from the other processor. Whenever the other processor's lock requests arrives at the head of the queue, there is a need for a change in the lock holder, i.e., to provide the lock to the lock requesting processor.

[0057] If no change in the lock holder is needed, the lock owning adapter begins to conduct the requested access of the shared resource (step **412**). This access operation is the "current" operation. After step **412**, the current access operation continues in steps **418** and **420** until finished. When the current access operation is finished, step **426** checks for receipt of another host access request from the host of the lock-owing adapter for the same subpart of the shared resource. When another host access request for this subpart is received, the new operation becomes the current access operation (step **424**) and then control passes back to step **412**, as discussed above.

[0058] On the other hand, if step **426** finds no more access requests, the lock holding adapter releases the lock (step **422**) and then returns to step **406**. Then, step **406** and the subsequent steps are performed as discussed above.

[0059] In contrast to the foregoing sequence, whenever step **407** determines that the lock holder must be changed, the adapters **154**, **156** effectively change the lock holder in step **408**. In the case of two adapters **154**, **156** (as illustrated), this involves electing the non-lock-holding adapter to be the new lock holder. In the case of three or more processors, the processors may cooperatively elect a new lock holder using a suitably fair arbitration scheme, such as enqueing adapters' lock requests and processing the requests sequentially, etc. In response to step **408**, the adapters configure their respective lock tables to reflect the newly elected lock holder, as shown by step **410**.

[0060] The lock tables are adjusted as follows. The new lock holder configures its lock table to show the involved shared resource subparts in the LOCAL state. In contrast, the non-lock-holder configures its lock table to show these subparts in the REMOTE state. Thus, rather than being replicated, the lock tables **172, 174** are "coordinated." Having configured their lock tables in step **410**, the adapters then operate so as to honor contents of the lock tables. Namely, the lock-holding adapter conducts the access to the exclusion of the non-lock-holding adapter.

[0061] The foregoing process continues, with host access requests being received and processed, and changes in the lock holder being made when necessary, as shown above.

More Detailed Example

[0062] The following discussion, with reference to FIGS. **4A-12**, further illustrates the invention by describing a detailed embodiment. Although the invention may be implemented with more adapters, the present example describes an especially valuable embodiment involving a system with managed access to shared digital storage among two adapters. This embodiment is described by disclosing various routines, which are performed by the adapters **154, 156**.

Terminology

[0063] According to the invention, each processor maintains a lock table with multiple entries, each entry corresponding to a subpart of the shared resource. In the illustrated example, each subpart (a lock table entry) concerns an address range of the shared storage, and may vary in size.

[0064] Along with each address range (subpart), a lock table lists its adapter's state for that subpart, which concerns the status of that adapter's possession of a lock on that subpart. Each adapter has a certain state for each different subpart. As explained below, an adapter's state may vary from subpart to subpart. Also, the two adapters **154, 156** may have the same or a different state regarding the same address range. When a lock has been granted, the adapter owning the lock is the "LOCAL" adapter, and the non-owning adapter is the "REMOTE" adapter. The adapter owning the lock has exclusive access to the relevant subpart of the shared resource, on behalf of itself or as a conduit for its attached host(s). From the perspective of one adapter, the states include:

[0065] 1. FREE—The lock is presently not granted to any adapter.

[0066] 2. LOCAL—The lock has been granted for use by this adapter. The LOCAL state may be further divided into various sub-states if desired.

[0067] 3. REMOTE—The lock has been granted to the other adapter. The REMOTE state may be further divided into various sub-states if desired.

[0068] 4. REQ—The LOCAL adapter has a request in progress to the REMOTE adapter for this lock.

[0069] As shown in **FIG. 4**A, the adapters exchange various "messages," and the hosts send "inputs" to the adapters. Adapters also self-generate certain "inputs." More specifically, the "messages" (adapter-to-adapter) include:

[0070] 1. LRQ—(Lock Request) This is a request filed by one adapter for a lock on an associated shared resource subpart.

[0071] 2. LRL—(Lock Release) This is a message returned by a LOCAL adapter relinquishing its lock on a shared resource subpart.

[0072] 3. LG—(Lock Grant) This is a message returned by one adapter agreeing that the other adapter can have the lock, thereby affirmatively completing the other adapter's lock request (LRQ).

[0073] There are also various "input", which arise externally from an attached host and/or internally from the adapter itself. These input include:

[0074] 1. OP—(Host Lock Request Input) This is a lock request from a host seeking access to a specified subpart of the shared resource. The receipt of this input signifies the very first step in the process of an adapter obtaining a lock on a subpart.

[0075] 2. DONE—This input is received by an adapter (1) from an attached host when the host is finished using the locked address range of the shared resource, or (2) from itself when the adapter has finished processing an ABORT input, as discussed below.

[0076] 3. ABORT—This self-generated input occurs when a "timeout" associated with a lock occurs, as discussed below.

[0077] The source and movement of messages and inputs are shown diagrammatically in **FIG. 4A**. As explained below, each adapter's lock table includes a queue for each subpart of the shared resource. The queues are used to serialize the processing of the inputs and certain messages applicable to that address range, from the standpoint of the adapter associated with that queue.

[0078] Certain events constitute "stimuli," which cause an adapter to emerge from a "wait" processing state and take certain action. Various situations are discussed below in which processors enter a "wait" state. The stimuli include:

[0079] 1. Arrival of a lock request (OP) input from an attached host.

[0080] 2. A lock request (OP) input arriving at the head of the queue.

[0081] 3. Arrival of a lock request (LRQ) message from the other adapter.

[0082] 4. A lock request (LRQ) message arriving at the head of the queue of a particular shared resource's subpart in an adapter's lock table.

[0083] 5. Arrival of a lock grant (LG) message from the other adapter.

[0084] 6. Arrival of a lock release (LRL) message from the other adapter.

[0085] 7. Receipt of a DONE input from an attached host.

[0086] 8. Receipt of an ABORT input from attached host.

[0087] **FIG. 4B** shows a time-based event diagram illustrating an exemplary exchange of signals during the process of acquiring a lock that is in FREE state. In this example, the passage of time is shown along a vertical axis, such that later events occur further downward and earlier events occur further upward in the diagram.

[0088] The first event occurs when a host sends a lock request input (OP) **450** to its adapter. The lock request input identifies a shared resource subpart by specifying a desired address range (not shown) of the shared resource. In response to the OP **450**, the adapter sends a lock request (LRQ) message **451** to the other adapter, requesting a lock on the desired address range. In response to the LRQ **451**, the second adapter returns a lock grant message (LG) **452**.

[0089] When the first adapter receives the LG **452**, it notifies its host that the lock has been granted by sending the host an OP GRANT message **453**. When the host learns that its lock is in place, it accesses the shared resource during a time period **454**. When the host finishes accessing the shared resource, it sends a DONE input **455** to the adapter. The adapter responds to the DONE input **455** by returning a lock release (LRL) message **456** to the second adapter, thereby relinquishing the lock on the present address range.

[0090] The communications protocol described above involves a minimum number of exchanges between the adapters, and thereby contributes to efficient system operation. Specifically, the process of one adapter obtaining and then relinquishing a lock is achieved with three inter-adapter messages: LRQ, LG, and finally LRL.

[0091] Furthermore, the use of the lock release message provides a number of advantages. First, this message helps conserve space in the lock table, the contents of which are discussed below. Namely, after a lock release operation, the released address range may be deleted from the lock table entirely, thereby conserving lock table space. In addition, the LRL message is conducive to fault tolerance of the system. In particular, by releasing locks in this manner, an adapter that fails is less likely to be holding the lock on an address range. Thus, recovery is expedited since it need not involve the failed adapter.

[0092] As another advantage of the foregoing communications protocol, no inter-adapter communications are required if the second adapter is not waiting for a lock on the subject address range. As discussed below, the first adapter need not issue the LRL message if the second adapter is not waiting for the lock. In this case, the first adapter can repeatedly perform the following sequence: receive OP from host, issue a GRANT of the OP, permit host to access resource, and receive DONE input. Thus, no inter-adapter communications are required at all.

Format of Lock Table

[0093] Table 1 (below) shows the various components of an exemplary lock table associated with one adapter. As shown in Table 1, the lock table contains one row for each address range (subpart) represented in the table, with each row listing the lock state, current token, and pending queue for that address range. The head of the queue in this example is the leftmost entry, with the end of the queue being the rightmost entry. If an address range has state FREE, it need not appear explicitly in the table unless its queue is non-empty. This helps conserve storage space.

TABLE 1

Exemplary Lock Table

ADDRESS RANGE [X]	LOCK STATE [STATE(X)]	CURRENT TOKEN [CURRENT(X)]	QUEUE [QUEUE(X)]
A1: 10–1024 bytes	LOCAL	Y1	(LRQ, A1, W1)
A2: 1025–2048 bytes	FREE	none	(OP, A2, 0)
A3: 2049–4096 bytes	LOCAL	Y2	(OP, A3, Y2), (OP, A3, 0)
A4: 4097–5120 bytes	REMOTE	W2	(OP, A4, Y3)
A5: 5121–6144 bytes	REQ	Y4	(OP, A5, Y4)
A6: 9520–9590 bytes	FREE	none	empty

[0094] The "lock state" column expresses the address range's lock state for the adapter owing the lock table, these states being FREE, REMOTE, LOCAL, or REQ. The "current token" column shows a present "token" for the associated address range. The token is a sequential code, such as an alphabetic, alphanumeric, or numeric code. Generally, as explained in greater detail below, tokens are used to uniquely identify messages, for example to ensure that a lock grant is issued specifically in response to a particular lock request. The "queue" column contains an ordered list of pending inputs and queued messages concerning the associated address range.

Perspective

[0095] With the foregoing background set forth, the following description illustrates a number of different operating sequences. Each sequence is performed by an adapter whenever that adapter receives certain stimuli. The adapters have like construction, and each is capable of performing any of the sequences, depending on the received stimuli. The following examples are discussed from the perspective of a "current" adapter that is performing the sequence, where the remaining adapter is called the "other" adapter.

Arrival of OP Input

[0096] **FIG. 5** describes the sequence **500** that an adapter performs in response to stimuli in the form of a host lock request input (OP). In step **502**, the adapter receives a host lock request input (OP). In the illustrated example, the input arrives in the form (OP, X), where "X" identifies the one of the subparts (address ranges) of shared storage **155**. The message of step **502** is generated by the adapter in response to a host request for a lock on the address range "X."

[0097] In step **504**, the adapter enqueues the input by storing it in the adapter's lock table, at the end of the queue associated with the address range "X." This queue may be called "Queue(X)." The input is enqueued in the format (OP, X, **0**), where OP represents the local lock request input, "X" identifies the address range, and "0" is a dummy token for the operation. The use of the dummy token is explained in greater detail below.

[0098] If there is no table entry for the address range X, step **504** creates the necessary table entry. After step **504**, the adapter waits (step **506**) for new stimuli.

OP Input Arrives at Head of Queue

[0099] **FIG. 6** describes the sequence **600** that an adapter performs in response to stimuli in the form of a local lock request input (OP) arriving at the head of the queue for a particular address range. In step **602**, the operation (OP, X, 0) arrives at the head of the queue for the address range "X," i.e., Queue(X). This operation will reside at the head of the queue for the address range X until the adapter receives a DONE or an ABORT input for the same address range X.

[0100] After step **602**, the adapter asks whether the state of the address range X is LOCAL (step **604**). If so, then the current adapter already owns the lock on the requested address range. In this case, step **620** replaces the operation's dummy token with the "current token." The current token for the address range X is obtained from the adapter's lock table; in the present example, each address range's current token is listed in the column "Current(X)."

[0101] After step **620**, with the adapter owning the lock on the address X, the adapter grants the local operation in step **622**, meaning that the requesting host is given access to the address range X. (This is also shown by the operation **453** in **FIG. 4B**.) After step **622**, the routine **600** progresses to step **624**, where the adapter enters a wait state **624**, awaiting another one of the prescribed stimuli.

[0102] In contrast to the foregoing description, if step **604** finds that the state of address range X is not LOCAL, then the current adapter does not own the lock on the requested address range. Namely, the state of address range X is either FREE, REMOTE, or REQ. In this event, step **606** is performed rather than step **620**. Step **606** generates a new token, referred to as "W." After generating the new token W, step **608** replaces the dummy token of the operation at the head of the queue with the new token W. Thus, (OP, X, 0) is replaced by (OP, X, W). Next, in step **610** the adapter sends a lock request to the other adapter so that the current operation (OP, X, W) can be completed. The lock request has the form (LRQ, X, W).

[0103] After step **610**, step **612** asks whether the state of the address range X is REMOTE. If so, step **612** advances to the wait state **624**, where the current adapter proceeds to wait for the other adapter to grant the requested lock. If step **612** finds that the state of the address range X is not REMOTE, the only remaining states are FREE and REQ. In either event, step **614** updates the address range X's entry in the lock table to reflect the new token W. After the table is updated to show W as Current(X), step **616** asks whether the address range X's state is REQ. If so, control advances to the wait state **624**. If the address range's state is not REQ, the only remaining state is FREE. In this event, step **618** changes X's state from FREE to REQ, and then progresses to step **624**.

Arrival of LRQ Message

[0104] **FIG. 7** describes the sequence **700** that an adapter performs in response to stimuli comprising receipt of a lock request message (LRQ) from the other adapter. In step **702**, the adapter receives a lock request message in the form (LRQ, X, Y). This message comprises a lock request, concerning the address range X, and includes the token Y.

[0105] After step **702**, step **704** asks whether the state of the identified address range at the current adapter is FREE. If so, step **714** grants the lock request to the other adapter by sending the lock grant message (LG, X, Y). This message includes a token (Y) matching the lock request's token. After step **714**, step **716** updates the current token shown in the sending adapter's lock table (Current(X)), to reflect the token Y used in the lock request and grant messages. Following step **716**, step **718** performs the internal bookkeeping necessary for the adapter to surrender the lock on the address range X. Namely, step **718** updates the adapter's lock table to show the state of address range X as REMOTE. After step **718**, the routine **700** ends, with the adapter going into a wait state **722**, pending arrival of the next stimuli.

[0106] In contrast, if the state of the address range X is not FREE, steps **706** and **708** proceed to ask whether the state is REQ or LOCAL. If the state is REQ, this means that the current adapter already has a request in progress for a lock on the address range X. In this case, both adapters are seeking locks on the same address range. Accordingly, step **712** performs arbitration to decide between the two adapters. The arbitration of step **712** may be achieved utilizing any mechanism having a fixed, unambiguous outcome that both adapters can reach without any intercommunication. As an example, the arbitration may be performed by permanently designating one adapter as the "winner," and the other as the "loser."

[0107] If the adapter performing step **700** is the loser, step **714** grants the lock to the other adapter, updates the current token, and sets the state of the address range X to REMOTE, as discussed above in steps **714**, **716**, and **718**. On the other hand, if the adapter performing step **700** is the winner, step **712** proceeds to step **720**, which enqueues the other adapter's lock request. This is performed by entering (LRQ, X, Y) in the queue column corresponding to the address range X. In the present example, operations are enqueued by placing them at the tail of the queue. However, enqueuing may alternatively be achieved by placing LRQ operations at the number-two position in the queue, the number-three position, or another predesignated position. Insertion at the number-one position (head of the queue) is avoided to prevent thrashing.

[0108] If step **708** finds that the state is LOCAL, step **720** enqueues the received lock request messages by storing (LRQ, X, Y) in the lock table row corresponding to the address range X. After step **720**, the adapter proceeds to step **722**, where it awaits further stimuli.

[0109] If step **708** finds that the state is not LOCAL, steps **704** and **706** dictate that the state must be REMOTE, such that the other adapter owns the lock on the address range X. In this case, the two adapters are confused as to which adapter owns the lock on the address range X. In this event, step **710** grants the lock to the other adapter by sending (LG, X, Current(X)). Following step **710**, the routine **700** ends, with the adapter going into a wait state **722**, awaiting the next stimulus.

LRQ Arrives at Head of Queue

[0110] **FIG. 8** describes the sequence **800** that an adapter performs in response to stimuli comprising arrival of an enqueued lock request message (LRQ) at the head of the queue. In step **802**, the lock request message (LRQ, X, Y) originating from the other adapter arrives at the head of the queue in the current adapter's lock table. In response, step

804 asks whether the state of the address range X is REQ. If so, the current adapter already has its own request for the lock in progress, so the adapter waits in step **806** to give its own request time to complete.

[**0111**] If the state is not REQ, step **808** asks whether the state is FREE. If so, step **818** grants the lock to the other adapter, by sending a lock grant message (LG, X, Y). Following step **818**, step **820** sets the lock table to show Y as the current token for the address range. Step **822** then sets the lock table to show REMOTE as the state of the address range X. Following step **822**, step **814** removes the lock request message from the queue, and then the adapter waits for further stimuli in step **816**.

[**0112**] In contrast, if the state is neither REQ nor FREE, the state must be REMOTE or LOCAL. In either case, step **808** advances to step **810**, which sends the other adapter a lock release message (LRL, X, Current(X)). Following step **810**, step **812** asks whether the state of the address range X is LOCAL. If so, the current adapter owns the lock on the address range X. In this case, the adapter proceeds to relinquish the lock to the other adapter. This is performed to ensure fair access to the address range X between the two adapters, preventing the local adapter from continually monopolizing the lock. More particularly, after an affirmative answer to step **812**, the adapter grants the lock, updates the token, and marks its own state as REMOTE. These tasks are performed in steps **818**, **820**, **822**, the details of which are discussed above.

[**0113**] If the address range X's state is not REQ, FREE, or LOCAL, it must be REMOTE, by the process of elimination. Therefore, the other adapter already owns the lock on the address range X, and the enqueued lock request id in error. In this event, step **812** proceeds to step **814**, which deletes the lock request (LRQ, X, Y) from the current adapter's queue, and proceeds to wait for the next stimulus in step **816**.

Arrival of LG Message

[**0114**] **FIG. 9** describes the sequence **900** that an adapter performs in response to stimuli comprising the receipt of a lock grant message (LG) from the other adapter. Namely, in step **902**, the current adapter receives a lock grant message (LG, X, Y). Step **904** asks if the state of the address range X is LOCAL. If so, the lock grant is meaningless, since the current adapter already owns the lock. In this case, the lock grant message is in error, and the current adapter proceeds to wait for the next stimulus in step **906**.

[**0115**] If the state is not LOCAL, step **908** asks if a request is in progress, i.e., the state is REQ. If no request is in progress, the lock is unneeded, and this situation may have arisen due to lost or misordered messages. In this case, the current adapter relinquishes the lock already granted. Specifically, step **910** returns a lock release message (LRL, X, Y) to the other adapter. After step **910**, the current adapter goes into a wait state **912**.

[**0116**] On the other hand, if step **908** finds a request in progress, step **914** asks whether the token of the lock request matches the current token (Current(X)) for the address range X. If so, the current adapter's lock request has been properly granted. In this case, the adapter in step **916** grants the operation at the head of the queue. In other words, the host source of the operation (OP) is given access to the address range X (as in step **622**). After step **916**, step **918** sets the state of the address range X to LOCAL, and then enters the wait state in step **912**.

Arrival of LRL Message

[**0117**] **FIG. 10** describes the sequence **1000** that an adapter performs in response to stimuli comprising receipt of a lock release message (LRL) from the other adapter. In step **1002**, the current adapter receives a lock release message (LRL, X, Y), originating from the other adapter. In response, step **1004** asks whether the state of the address range X is REMOTE, the only state within which the adapter would expect to receive a lock release message. If the state is not REMOTE, then the lock release is discarded, and the adapter proceeds to the wait state **1006**.

[**0118**] On the other hand, if the state is REMOTE, then a lock release is expected, but it is still necessary to verify that the lock release's token matches the address range's current token. In this case, step **1008** asks whether the token Y of the received (LRL, X, Y) matches Current(X). If not, step **1010** grants the lock to the other adapter by sending it (LG, X, Current(X)). This LG will prompt the other adapter to send (step **910**) a matching (LRL, X, Current(X)) in case the non-matching LRL is the result of lost messages and the other adapter does not have X in state LOCAL. This is an example of a response designed to recover from and tolerate intermittent communication failures. After step **1010**, the routine **1000** proceeds to the wait step **1006**.

[**0119**] If the tokens match, however, step **1012** asks whether the operation pending at the head of the address range X's queue contains a local lock request with a valid, non-dummy token. If not, then there is no local operation awaiting the lock and the lock release message (LRL) results in freeing of the address range. Specifically, the adapter sets the address range's state to FREE in step **1014**. If the head of the address range X's queue does contain a local lock request with a valid token, step **1018** updates the current adapter's current token to match the queued local lock request's token. In this example, the host's lock request is (OP, X, W), and the current token is updated to token W. Since the current adapter presumably had sent (LRQ, X, W) in step **610**, steps **1018** and **1020** prepare the adapter to receive the matching (LG, X, W) that will be sent by the other adapter in step **818** when (LRQ, X, W) reaches the head of its queue for X (Queue(X)). After step **1018**, step **1020** sets the address range's state to REQ, and then proceeds to wait in step **1016**.

Receipt of DONE Condition

[**0120**] **FIG. 11** describes the sequence **1100** that an adapter performs in response to stimuli comprising arrival of a DONE input. In step **1102**, the adapter receives an input (DONE, X). This input arrives from the host when it completes its current operation on the address range X, or it is generated by the current adapter because of a timeout or another condition requiring an operation in progress to abort.

[**0121**] After step **1102**, step **1104** deletes local lock request (OP) at the head of the address range X's queue. Then, step **1106** asks whether the address range's state is REQ. If so, the current adapter in step **1114** sends the other adapter a lock release message (LRL, X, Current(X)), sets the address range's state to FREE (step **1116**), and enters the wait state **1110**.

[**0122**] If the address range X's state is not REQ, step **1108** asks whether the state is LOCAL. If the state is LOCAL, step **1112** asks whether the queue for the address range X is empty. If the queue is not empty, the sequence **1100** enters the wait state **1110**. If the queue is empty, however, the current adapter sends the other adapter a lock release message (LRL, X, Current(X)) (step **1114**), sets the address range's state to FREE (step **1116**), and enters the wait state **1110**. This method allows the current adapter to perform multiple operations on the same address range without the need to exchange any messages with the other adapter.

[**0123**] In contrast to the foregoing description, if steps **1106, 1108** find that the state is neither REQ nor LOCAL, then the operation has already completed and this DONE is redundant. In this case, the sequence **1100** waits in step **1110**.

Receipt of ABORT Condition

[**0124**] **FIG. 12** describes the sequence **1200** that an adapter performs in response to stimuli comprising arrival of an abort input. In step **1202**, the adapter receives an (ABORT, X) input, originating from one of the adapter's hosts. The ABORT input may result from various conditions, such as a timeout, failure of an adapter, failure of inter-adapter communications, loss of power, etc. After step **1202**, step **1206** asks whether the received abort input is directed at the local lock request operation (OP) at the head of the queue. If not, the adapter generates a DONE input in step **1208**. Otherwise, step **1204** asks whether the address range X's state is LOCAL. If so, step **1206** takes steps to make the shared resource **155**"safe," e.g., consistent, complete, etc. In the case of a data storage resource, step **1206** may complete the operation in progress, reverse stored data back to a previous state, calculate parity, etc. After step **1206**, step **1208** generates (DONE, X) as input.

[**0125**] If step **1204** finds a state other than LOCAL, then the operation to be aborted has not started and cannot have placed the resource in an unsafe (incomplete) condition. In this case, the routine **1200** generates (DONE, X) as input in step **1208**.

Additional Features Supporting Liveness

[**0126**] The invention may also provide various features to help ensure the "liveness" of the processing system. Liveness refers to the system's robust resistance to hanging up or otherwise becoming inoperative due to a failure of a subcomponent. As shown below, these liveness features include a "retry" facility and a "timeout" facility.

[**0127**] The retry facility may be implemented by various measures to ensure that lock requests are eventually repeated. As one example, the adapters may be programmed to review their lock tables for address ranges that are in the REQ or REMOTE state, and have an OP input with a valid token at the head of the queue. This situation indicates that the pending OP input is waiting for the lock. The lock table review may be conducted periodically, whenever a new OP input is received, or on another sufficiently frequent basis. As another alternative, each adapter may associate a timer with each LRQ message sent. In this embodiment, the adapter resends the LRQ message if the lock is not granted before the timer expires.

[**0128**] In contrast to the retry facility, the timeout facility is provided to help tolerate failures in host-adapter interaction. Such failure situations may arise from a failed host, a failed shared resource, etc. The timeout facility associates a timer with each new host lock request input (OP). The timer may be initiated, for example, as part of step **504** (**FIG. 5**). The timer is satisfied (and thus removed) whenever the OP message completes to fruition (marked by the host submitting a DONE input). Removal of the timer may occur, for instance, in step **1104** (**FIG. 11**). If the timer runs out before completing successfully, the timer causes an ABORT input to be issued. This prevents starving of the other adapter and its hosts due to an unresponsive adapter, host, or address range.

Other Embodiments

[**0129**] While the foregoing disclosure shows a number of illustrative embodiments of the invention, it will be apparent to those skilled in the art that various changes and modifications can be made herein without departing from the scope of the invention as defined by the appended claims. Furthermore, although elements of the invention may be described or claimed in the singular, the plural is contemplated unless limitation to the singular is explicitly stated.

What is claimed is:

1. A method for managing access to a shared resource in a computing system, including multiple processors each coupled to the shared resource, the processors being coupled to one or more hosts, the method comprising operations of:

each processor separately storing a corresponding lock table listing one or more subparts of the shared resource, where each lock table also lists in association with each subpart a state selected from a state group including a LOCAL state and a REMOTE state;

in response to an access request one of the hosts, the access request identifying one or more subparts of the shared resources, the processors awarding a lock on all identified subparts by electing a single processor to have exclusive access to the identified subparts;

in response to the election, at a first time all non-lock-holding processors configuring their lock tables to show the identified subparts in the REMOTE state, and no earlier then the first time the lock-holding processor configuring its lock table to show the identified subpart in the LOCAL state; and

each processor refraining from accessing a subpart of the shared resource unless the processor's lock table indicates a LOCAL state for that subpart.

2. The method of claim 1, the lock-holding processor configuring its lock table to show the identified subpart in the LOCAL state after the first time.

3. The method of claim 1, each processor storing its corresponding lock table in non- volatile storage.

4. The method of claim 1, the shared resource comprising one or more digital data storage devices.

5. The method of claim 1, the processors of the system being two in number.

6. The method of claim 1, the processors of the system being two in number, and including first and second processors, the electing operation including:

responsive to the first processor receiving a request to access a particular subpart, where the first processor's lock table indicates a REMOTE state for that subpart, the first processor transmitting a lock request message to the second processor;

responsive to receipt of a lock request message concerning the subpart, the second processor configuring its lock table to indicate the REMOTE state for the identified subpart and then transmitting a lock grant message to the first processor; and

responsive to receipt of a lock grant message concerning the subpart, the first processor configuring its lock table show a LOCAL state for the identified subpart.

7. The method of claim 6, where each message is accompanied by a token, and the operations further comprise:

the first processor determining whether tokens of the lock request and lock grant messages match, and if not, aborting the operation of configuring the first processor's lock table show a LOCAL state for the subpart.

8. The method of claim 1, where the state group further includes a FREE state.

9. The method of claim 8, where the electing operation further includes:

responsive to a processor completing access to a subpart of the shared resource, the processor transmitting a lock release message to the other processors, and then each processor configuring its lock table to indicate the FREE state for the subpart.

10. The method of claim 9, where the configuring of the lock table to indicate the FREE state comprises the processor removing representation of the subpart from the lock table.

11. The method of claim 8, the processors of the system being two in number, and including first and second processors, the electing operation comprising:

the first processor transmitting a lock request message to the second processor, the lock request naming the identified subpart of the shared resource;

the second processor consulting its lock table to determine the state of the identified subpart, and in response to the lock table indicating a FREE state of the subpart, the second processor transmitting a lock grant message to the first processor, and then configuring the second processor's lock table to show a REMOTE state for the identified subpart; and

the first processor receiving the lock grant message, and in response configuring the first processor's lock table to show a LOCAL state for the identified subpart.

12. The method of claim 1, the processors of the system being two in number, and including first and second processors, the electing operation including:

responsive to the first processor receiving a request to access a particular subpart, where the first processor's lock table indicates a REMOTE state for that subpart, the first processor transmitting a lock request message to the second processor;

responsive to the first processor failing to receive a lock grant message within a predetermined time, the first processor retransmitting the lock request message to the second processor.

13. The method of claim 1, the processors of the system being two in number, and including first and second processors, the electing operation including:

responsive to the first processor receiving a request to access a subpart, where the first processor's lock table indicates a REMOTE state for that subpart, the first processor transmitting a lock request message to the second processor;

responsive to the lock request message, the second processor representing the lock request in a queue;

the second processor sequentially processing the queued messages, and upon reaching the queued lock request, the second processor configuring its lock table to indicate the REMOTE state for the subpart and then transmitting a lock grant message to the first processor; and

responsive to receipt of a lock grant message concerning an identified subpart, the first processor configuring its lock table show a LOCAL state for the identified subpart.

14. The method of claim 1, the processors being two in number, and including first and second processors, the operations further comprising:

responsive to the first processor receiving a host request to access a first subpart of the shared resource while the lock table of the first processor shows the first subpart in the REMOTE state, the first processor transmitting a lock request message to the second processor in association with the first subpart.

15. The method of claim 14, further comprising:

the first processor retransmitting the lock request to the second processor according to a predetermined schedule until the second processor grants the requested lock on the first subpart.

16. The method of claim 14, where:

each processor maintains a queue of pending operations; and

responsive to the lock request, the second processor places a representation of the lock request in the queue of the second processor.

17. The method of claim 1, where:

the processors maintain respective queues of pending operations, and where each processor is responsive to host requests to access a subpart of the shared resource while the lock table of the processor shows the subpart in the REMOTE state by sending a lock request message to the other processor; and

the electing operation comprises, responsive to a processor's receipt of an access request from one of the hosts involving a first subpart of the shared resource, determining whether the lock table of the processor lists the subpart in the LOCAL state and the processor's queue is free from any lock requests from the second processor, and if so, the processor proceeding to satisfy the host access request without sending any messages to the other processor.

18. The method of claim 1, further comprising:

in response to a processor receiving a host access request, the processor setting a timer, satisfied by completion of the host access request; and

responsive to unsatisfied expiration of the timer, the processor aborting the host access request.

19. The method of claim 1, where:

the processors maintain respective sequential queues of pending operations;

the processors are two in number, and include first and second processors, one of the processors being predesignated as a winner and the other being predesignated as a loser; and

responsive to each processor receiving a lock request from the other processor, where each processor has sent an unsatisfied lock request to the other processor, the loser processor granting a lock on the subpart to the winner processor, and the winner processor waiting for the lock grant and enqueing the loser processor's lock request.

20. A signal-bearing medium tangibly embodying a program of machine-readable instructions executable by a digital data processing machine to perform operations to manage one processor in a multiple processor computing system, the processors having access to a shared resource, the operations comprising:

the processor storing a lock table listing one or more subparts of the shared resource, the lock table also listing in association with each subpart a state selected from a state group including a LOCAL state and a REMOTE state;

in response to an access request from one of the hosts, the access request identifying one or more subparts of the shared resource, the processor cooperating with the other processors to award a lock on all identified subparts by electing a single processor to have exclusive access to the identified subparts;

in response to the election,

if the processor is not elected, the processor configuring its lock table to show the identified subpart in the REMOTE state;

if the processor is elected, the processor configuring its lock table to show the identified subpart in the LOCAL state; and

the processor refraining from accessing a subpart of the shared resource unless the processor's lock table indicates the LOCAL state for that subpart.

21. The medium of claim 20, the processor storing its lock table in non-volatile storage.

22. The medium of claim 20, the shared resource comprising one or more digital data storage devices.

23. The medium of claim 20, the processors of the system being two in number.

24. The medium of claim 20, where the state group further includes a FREE state.

25. A multiple processor computing system, comprising:

a shared resource having multiple subparts; and

multiple processors coupled to one or more hosts, each processor being coupled to the shared resource, where the processors are programmed to perform operations to cooperatively utilize the resource, the operations comprising:

each processor separately storing a corresponding lock table listing one or more subparts of the shared resource, where each locktable also lists in association with each subpart a state selected from a state group including a LOCAL state and a REMOTE state;

in response to an access request from one of the hosts, the processors awarding a lock on all identified subparts by electing a single processor to have exclusive access to the identified subparts;

in response the election, at a first time all non-lock-holding processors configuring their lock tables to show the identified subparts in the REMOTE state, and no earlier then the first time the lock-holding processor configuring its lock table to show the identified subpart in the LOCAL state; and

each processor refraining from accessing a subpart of the shared resource unless the processor's lock table indicates a LOCAL state for that subpart.

26. The system of claim 25, the lock-holding processor configuring its lock table to show the identified subpart in the LOCAL state after the first time.

27. The system of claim 25, each processor storing its corresponding lock table in non-volatile storage.

28. The system of claim 25, the shared resource comprising one or more digital data storage devices.

29. The system of claim 25, the processors of the system being two in number.

30. The system of claim 25, the processors of the system being two in number, and including first and second processors, the electing operation including:

responsive to the first processor receiving a request to access a particular subpart, where the first processor's lock table indicates a REMOTE state for that subpart, the first processor transmitting a lock request message to the second processor;

responsive to receipt of a lock request message concerning the subpart, the second processor configuring its lock table to indicate the REMOTE state for the subpart and then transmitting a lock grant message to the first processor; and

responsive to receipt of a lock grant message concerning an identified subpart, the first processor configuring its lock table show a LOCAL state for the identified subpart.

31. The system of claim 30, where each message is accompanied by a token, and the operations further comprise:

the first processor determining whether tokens of the lock request and lock grant messages match, and if not, aborting the operation of configuring the first processor's lock table show a LOCAL state for the subpart.

32. The system of claim 25, where the state group further includes a FREE state.

33. The system of claim 32, where the electing operation further includes:

responsive to a processor completing access to a subpart of the shared resource, the processor transmitting a lock release message to the other processors, and then each processor configuring its lock table to indicate the FREE state for the subpart.

34. The system of claim 33, where the configuring of the lock table to indicate the FREE state comprises the processor removing representation of the subpart from the table.

35. The system of claim 32, the processors being two in number, and including first and second processors, the electing operation comprising:

the first processor transmitting a lock request message to the second processor, the lock request naming the identified subpart of the shared resource;

the second processor consulting its lock table to determine the state of the identified subpart, and in response to the lock table indicating a FREE state of the subpart, the second processor transmitting a lock grant message to the first processor, and then configuring the second processor's lock table to show a REMOTE state for the identified subpart; and

the first processor receiving the lock grant message, and in response configuring the first processor's lock table to show a LOCAL state for the identified subpart.

36. The system of claim 25, the processors of the system being two in number, and including first and second processors, the electing operation including:

responsive to the first processor receiving a request to access a particular subpart, where the first processor's lock table indicates a REMOTE state for that subpart, the first processor transmitting a lock request message to the second processor;

responsive to the first processor failing to receive a lock grant message within a predetermined time, the first processor retransmitting the lock request message to the second processor.

37. The system of claim 25, the processors being two in number, and including first and second processors, the electing operation including:

responsive to the first processor receiving a request to access a subpart, where the first processor's lock table indicates a REMOTE state for that subpart, the first processor transmitting a lock request message to the second processor;

responsive to the lock request message, the second processor representing the lock request in a queue;

the second processor sequentially processing the queued messages, and upon reaching the queued lock request, the second processor configuring its lock table to indicate the REMOTE state for the subpart and then transmitting a lock grant message to the first processor; and

responsive to receipt of a lock grant message concerning an identified subpart, the first processor configuring its lock table show a LOCAL state for the identified subpart.

38. The system of claim 25, the processors being two in number, and including first and second processors, the operations further comprising:

responsive to the first processor receiving a host request to access a first subpart of the shared resource while the lock table of the first processor shows the first subpart in the REMOTE state, the first processor transmitting a lock request message to the second processor in association with the first subpart.

39. The system of claim 38, the operations further comprising:

the first processor retransmitting the lock request to the second processor according to a predetermined schedule until the second processor grants the requested lock on the first subpart.

40. The system of claim 38, where:

each processor maintains a queue of pending operations; and

responsive to the lock request, the second processor places a representation of the lock request in the queue of the second processor.

41. The system of claim 25, where:

the processors maintain respective queues of pending operations, and where each processor is responsive to host requests to access a subpart of the shared resource while the lock table of the processor shows the subpart in the REMOTE state by sending a lock request message to the other processor; and

the electing operation comprises, responsive to a processor's receipt of an access request from one of the hosts involving a first subpart of the shared resource, determining whether the lock table of the processor lists the subpart in the LOCAL state and the processor's queue is free from any lock requests from the second processor, and if so, the processor proceeding to satisfy the host access request without sending any messages to the other processor.

42. The system of claim 25, the operations further comprising:

in response to a processor receiving a host access request, the processor setting a timer, satisfied by completion of the host access request; and

responsive to unsatisfied expiration of the timer, the processor aborting the host access request.

43. The system of claim 25, where:

the processors maintain respective sequential queues of pending operations;

the processors are two in number, and include first and second processors, one of the processors being predesignated as a winner and the other being predesignated as a loser; and

responsive to each processor receiving a lock request from the other processor, where each processor has sent an unsatisfied lock request to the other processor, the loser processor issuing a lock on the subpart to the winner processor, and the winner processor waiting for the lock grant and enqueing the loser processor's lock request.

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