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Canadian Intellectual Property Office

CA 2964590 C 2020/01/28

(11)(21) 2 964 590

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(86) Date de dépôt PCT/PCT Filing Date: 2015/10/19
(87) Date publication PCT/PCT Publication Date: 2016/04/28
(45) Date de délivrance/Issue Date: 2020/01/28
(85) Entrée phase nationale/National Entry: 2017/04/12
(86) N° demande PCT/PCT Application No.: US 2015/056159
(87) N° publication PCT/PCT Publication No.: 2016/064705
(30) Priorité/Priority: 2014/10/20 (US62/065,941)

(51) Cl.Int./Int.Cl. *G06F 11/07* (2006.01),
G06F 9/52 (2006.01)

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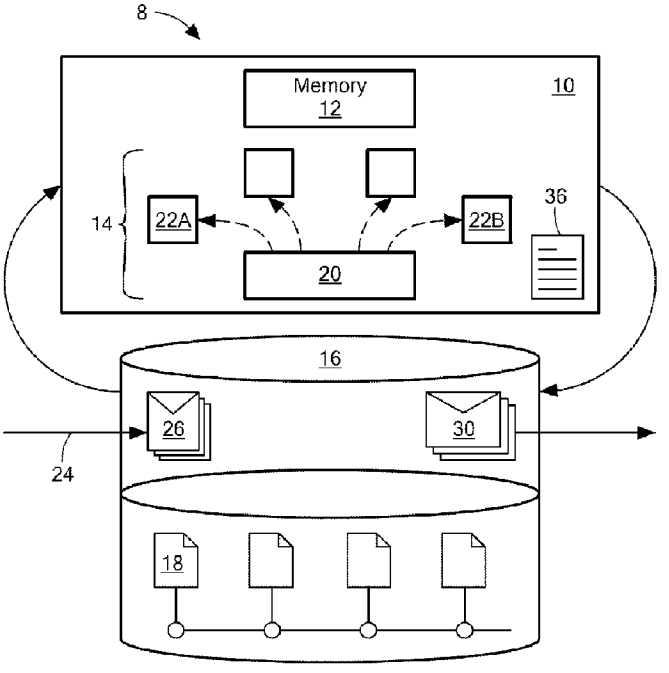
(54) Titre : RECUPERATION ET TOLERANCE AUX PANNES DANS DES CONDITIONS D'INDETERMINISME COMPUTATIONNEL

(54) Title: RECOVERY AND FAULT-TOLERANCE UNDER COMPUTATIONAL INDETERMINISM



(57) Abrégé/Abstract:
A method for promoting fault tolerance and recovery in a computing system including at least one processing node includes promoting availability and recovery of a first processing node, by, at the first processing node, generating first spawn using a spawner that has been assigned a first generation-indicator so that its spawn inherits the first generation indicator, beginning a checkpoint interval to generate nodal recovery information, suspending the spawner from generating spawn, assigning, to the spawner, a second generation-indicator that differs from the first one, resuming the spawner, so that it generates second spawn that inherits the second generation-indicator, controlling an extent to which the second spawn writes to memory, and after committing nodal recovery information acquired during the checkpoint to durable storage, releasing control over the extent to which the second spawn can write to memory.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 April 2016 (28.04.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/064705 A1

(51) International Patent Classification:
G06F 11/14 (2006.01) *G06F 9/52* (2006.01)

(21) International Application Number:
PCT/US2015/056159

(22) International Filing Date:
19 October 2015 (19.10.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/065,941 20 October 2014 (20.10.2014) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) **Title**: RECOVERY AND FAULT-TOLERANCE UNDER COMPUTATIONAL INDETERMINISM

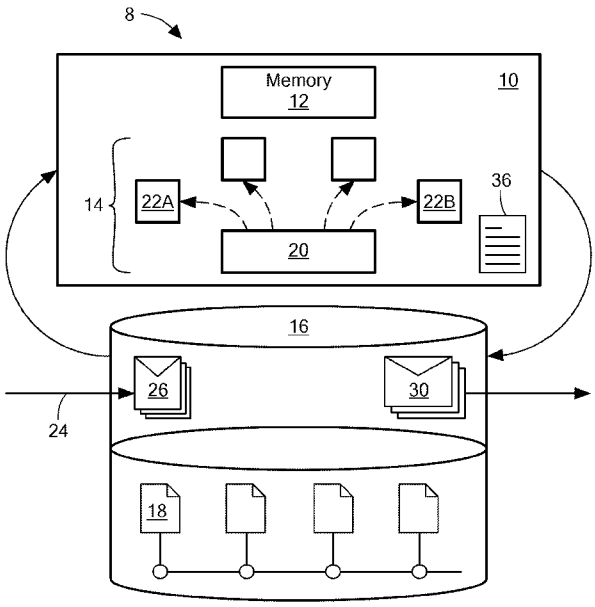


FIG. 1

(57) **Abstract**: A method for promoting fault tolerance and recovery in a computing system including at least one processing node includes promoting availability and recovery of a first processing node, by, at the first processing node, generating first spawn using a spawner that has been assigned a first generation-indicator so that its spawn inherits the first generation indicator, beginning a checkpoint interval to generate nodal recovery information, suspending the spawner from generating spawn, assigning, to the spawner, a second generation-indicator that differs from the first one, resuming the spawner, so that it generates second spawn that inherits the second generation-indicator, controlling an extent to which the second spawn writes to memory, and after committing nodal recovery information acquired during the checkpoint to durable storage, releasing control over the extent to which the second spawn can write to memory.

WO 2016/064705 A1

RECOVERY AND FAULT-TOLERANCE UNDER COMPUTATIONAL INDETERMINISM

BACKGROUND

This description relates to recovery and fault-tolerance in the presence of computational indeterminism.

Computational systems occasionally fail for a variety of reasons. When such systems fail, data can be lost. It is desirable to take measures to prevent, or at least minimize, such data loss.

Examples of such measures include ACID (Atomic, Consistent, Isolated until committed, Durable when committed) transactions in databases. These known measures are extremely robust. They can be made to meet very high standards of correctness, while also being made fault tolerant.

However, all of this robustness comes at a cost. Known methods for guarding against failure have high latency and sometimes cause extended periods during which the apparatus is unavailable. Thus, they are less than optimal for high-volumes of transactions.

In addition, some known methods require deterministic computation. In deterministic computation, the order in which tasks are performed is fixed, and the result of a computation remains the same each time it is carried out. It is not clear how these known methods can be adapted to efficiently handle non-deterministic computational environments.

Additional complexity arises when a computing apparatus includes multiple processing nodes that cooperate with each other. In such an apparatus, it is possible for one node of the apparatus to fail, and others to keep working. When that failed node recovers, this is no guarantee that it has restored itself to a state that the other nodes expect it to be in.

SUMMARY

In one aspect, the invention features a method for enhancing fault tolerance and recovery in a computing system including at least one processing node, said method including: enhancing availability and recovery of a first processing node,

including, at the first processing node, executing a spawner at said node, wherein said spawner, in the course of execution, generates a first spawn, wherein the spawner implements a process, with an associated expected spawner lifetime, configured to generate one or more spawn processes, including the first spawn, that are each associated with a respective expected lifetime shorter than the expected spawner lifetime, and which are configured to be suspended if, following a checkpoint event and suspension of the spawner, the respective one or more spawn processes are still executing after a pre-determined interval measured from occurrence of the checkpoint event and suspension of the spawner, wherein at least one of the one or more spawn processes terminates before the end of the pre-determined interval, wherein executing said spawner includes assigning, to said spawner, a first generation indicator, wherein said first spawn inherits said first generation indicator; beginning a checkpoint interval, at the end of which nodal recovery information, which is usable for recovery of said node, is committed to durable storage, wherein beginning said checkpoint interval includes: suspending said spawner from generating spawn, assigning, to said spawner, a second generation indicator that differs from said first generation indicator, resuming said spawner, thereby enabling said spawner to generate a second spawn, wherein said second spawn inherits said second generation indicator, and controlling an extent to which said second spawn writes to memory; and after committing said nodal recovery information, releasing control over said extent to which said second spawn can write to memory.

In some practices, controlling an extent to which the second spawn writes to memory includes preventing the second spawn from consummating a write to the memory. Among these are practices that further include permitting the second spawn to queue the write to memory for eventual consummation thereof after the recovery information has been committed.

In other practices, controlling an extent to which the second spawn writes to memory includes determining that the write operation is a commutable operation, and allowing consummation of the commutable operation. Among these practices are those in which determining that the write operation is a commutable operation includes determining that the write operation includes incrementing a variable, and those in which determining that the write operation is a commutable operation

includes determining that the write operation includes inserting a record at a specified location.

Also among the practices of the invention are those that further include, after suspending the spawner, setting a deadline, thereby providing time for any spawn having the first task generation-indicator to execute to completion, and avoiding overhead associated with having to save states of the spawn having the first generation-indicator. Among these practices are those that include suspending the first spawn if the first spawn is still executing as of the deadline, and those that include enabling the first spawn to avoid suspension as a result of having failed to complete execution by the deadline, for example by changing the first task generation-indicator to the second task generation-indicator in the first spawn if the first spawn is still executing as of the deadline.

In those cases in which the first node has a nodal-generation indicator, additional practices of the invention include causing a spawn to become a migrant that migrates to a second node, wherein the second node has a nodal-generation indicator. Among these practices are those in which the nodal-generation counter of the second node indicates that the second node is in a younger generation than the first node, in which case the method further includes youthening the migrant, either by immigration-side youthening of the migrant, or by emigration-side youthening of the migrant.

In some cases, the first node is a node in a multi-node system in which each node has a nodal generation-count, and the multi-node system includes at least a second node. In these cases, there are practices of the invention in which, upon recovery following a failure of the second node, the first node rolls back to a state that corresponds to a nodal-generation count of the second node.

In other cases, the first node is a node in a multi-node system in which each node has a nodal generation-count, and the multi-node system includes at least a second node. In these cases, some practices of the invention include, upon recovery following a failure of the first node, having the first node roll forward to a state that corresponds to a nodal-generation count of the second node by restoring committed work from a checkpoint and restoring uncommitted work from a journal.

In those cases in which the first node is a node in a multi-node system in which each node has a nodal generation-count, practices of the invention include those in which the first node carries out certain acts. These include receiving, from a master node, a message indicating that a checkpoint is to be carried out, in response, youthening a nodal generation count of the first node, suspending spawners from generating spawn, saving spawner recovery information for recovering spawner states, resuming the spawners, determining that no further older-generation immigrants are expected at the first node, and in response to the determination, committing, to the durable storage, the nodal recovery information. Among these practices are those that also include setting a deadline, and, upon lapse of the deadline, suspending all older-generation spawn that are still executing while younger-generation spawn continue to execute.

In some cases, the first node is a node in a multi-node system. In such cases, alternative practices of the invention include saving a replica copy of working memory of the first node at the second node, upon failure of the first node, temporarily using the replica copy for processing that would otherwise have been carried out by the first node, and, upon recovery of the first node, communicating, to the first node, information required to update memory in the first node so that subsequent computation can be carried out by the first node.

In another aspect, the invention features a computer program product stored in a non-transitory form on a computer-readable medium, for enhancing fault tolerance and recovery in a computing system including at least one processing node, the computer program product including instructions for causing a computing system to: enhance availability and recovery of a first processing node, including, at a first processing node, executing a spawner at said node, wherein said spawner, in the course of execution, generates a first spawn, wherein the spawner implements a process, with an associated expected spawner lifetime, configured to generate one or more spawn processes, including the first spawn, that are each associated with a respective expected lifetime shorter than the expected spawner lifetime, and which are configured to be suspended if, following a checkpoint event and suspension of the spawner, the respective one or more spawn processes are still executing

after a pre-determined interval measured from occurrence of the checkpoint event and suspension of the spawner, wherein at least one of the one or more spawn processes terminates before the end of the pre-determined interval, wherein executing said spawner includes assigning, to said spawner, a first generation indicator, wherein said first spawn inherits said first generation indicator; beginning a checkpoint interval, at the end of which nodal recovery information, which is usable for recovery of said node, is committed to durable storage, wherein beginning said checkpoint interval includes: suspending said spawner from generating spawn, assigning, to said spawner, a second generation indicator that differs from said first generation indicator, resuming said spawner, thereby enabling said spawner to generate a second spawn, wherein said second spawn inherits said second generation indicator, and controlling an extent to which said second spawn writes to memory; and after committing said nodal recovery information, releasing control over said extent to which said second spawn can write to memory.

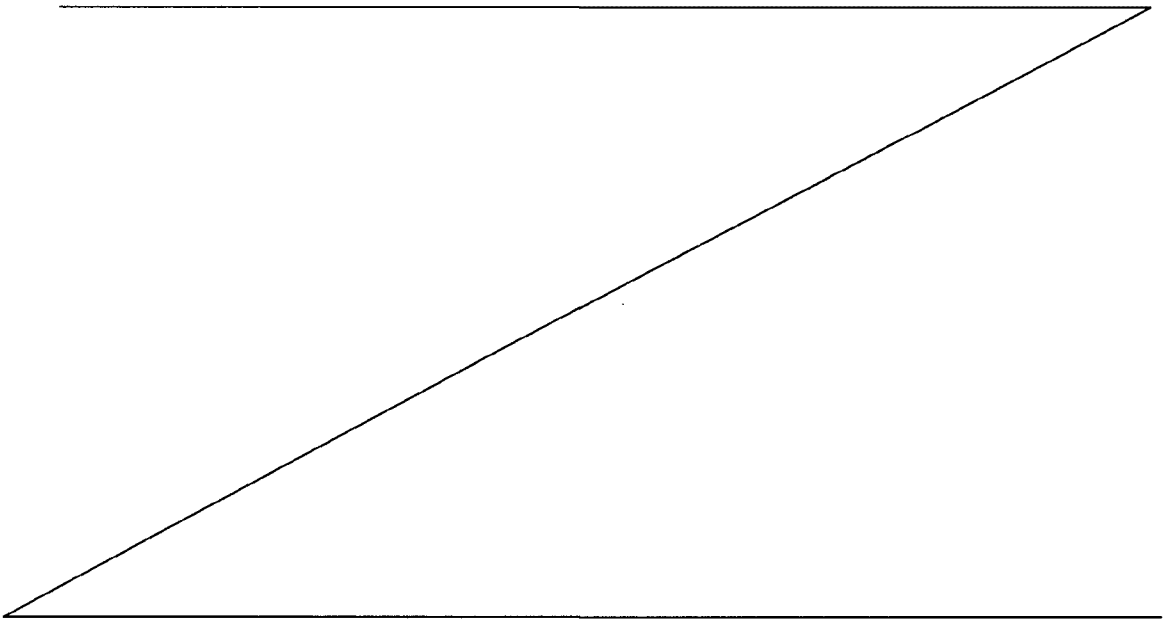
In yet another aspect, the invention features a data storage system including durable storage; and one or more processing nodes including least one processor configured to enhance availability and recovery of a first processing node, including, at the first processing node, executing a spawner at said node, wherein said spawner, in the course of execution, generates a first spawn, wherein the spawner implements a process, with an associated expected spawner lifetime, configured to generate one or more spawn processes, including the first spawn, that are each associated with a respective expected lifetime shorter than the expected spawner lifetime, and which are configured to be suspended if, following a checkpoint event and suspension of the spawner, the respective one or more spawn processes are still executing after a pre-determined interval measured from occurrence of the checkpoint event and suspension of the spawner, wherein at least one of the one or more spawn processes terminates before the end of the pre-determined interval,

wherein executing said spawner includes assigning, to said spawner, a first generation indicator, wherein said first spawn inherits said first generation indicator; beginning a

checkpoint interval, at the end of which nodal recovery information, which is usable for recovery of said node, is committed to durable storage, wherein beginning said checkpoint interval includes suspending said spawner from generating spawn, assigning, to said spawner, a second generation indicator that differs from said first generation indicator, resuming said spawner, thereby enabling said spawner to generate a second spawn, wherein said second spawn inherits said second generation indicator, and controlling an extent to which said second spawn writes to memory; and after committing said nodal recovery information, releasing control over said extent to which said second spawn can write to memory.

Aspects can have one or more of the following advantages.

The techniques for promoting fault tolerance and recovery described herein enable the computing system to remain highly available. By strategically relaxing certain ACID constraints, the computing system can still provide recoverability, but without the high overhead of more extreme measures. Thus, there are more computing resources available for useful work. Also, by controlling the extent to which spawn (e.g., operating system processes or threads) write to memory, useful work can still be accomplished during a checkpoint interval, while ensuring that integrity of the fault tolerance mechanisms is maintained. Thus, these techniques enhance the internal functioning of the computing system, both in the event of faults, and during normal fault-free operation.



BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a single-node computing apparatus for carrying our fault-tolerance and recovery in the presence of computational indeterminism;

FIG. 2 shows checkpoint intervals and working intervals encountered during operation of the node of FIG. 1;

FIG. 3 shows a method in which spawn are allowed to run to completion during the checkpoint interval of FIG. 2;

FIG. 4 shows a method in which a spawning process can continue to generate spawn during the checkpoint interval of FIG. 2;

FIG. 5 shows a method in which spawn can continue to work during a checkpoint interval by queuing writes to memory;

FIG. 6 shows a multi-node computing apparatus;

FIG. 7 shows two generations co-existing in a node from the apparatus of FIG. 7;

FIG. 8 shows method steps carried out by a slave node in response to a checkpoint message;

FIG. 9 shows method steps involving incrementing a migrant generation count;

FIG. 10 shows method steps for recovery after failure;

FIG. 11 shows a replica maintained at another node to enable more rapid recovery;

FIG. 12 shows a procedure for using the replica shown in FIG. 11 for rapid recovery; and

FIG. 13 shows an example of execution of the method shown in FIG. 5 in connection with multiple nodes as illustrated in FIG. 9.

DETAILED DESCRIPTION

FIG. 1 shows an example of a data processing system in which techniques for fault tolerance and recovery in the presence of computational indeterminism can be used. The data processing system includes a single-node computing apparatus **8**

having a node **10** that includes a working-memory **12**. Processes **14** running on that node **10** use this working-memory **12** to save their respective process states and to store intermediate results of their respective computations. In different embodiments, the processes **14** may be implemented as any of a variety of types of computing resources within an operating system running on the node **10**. For example, the processes **14** may be implemented as operating system 'processes' that have their own address space, or as operating system 'threads' that have their own execution context (e.g., stage, registers, etc.), or as some other type of 'task' that includes a sequence of operations to be performed but does not necessarily have a particular operating system process or thread dedicated to it.

Because the working-memory **12** is often volatile, it is prudent to periodically save its state in checkpoint files **18** stored in durable storage **16**. These checkpoint files **18** can be used to recover state information in case of an interruption in operation of the node **10**.

Among the processes **14** running on the node are spawners **20**. A "spawner" is a type of process that has, among its properties, the ability to generate one or more other processes. The processes that are generated by a spawner are referred to herein, both in the singular and in the plural, as "spawn." The act of generating such spawn is referred to by appropriate variants of the verb "to spawn." FIG. 1 shows a spawner **20** that has generated spawn **22A**, **22B**. A spawner **20** is generally a long-lived process, whereas the spawn **22A**, **22B**, although numerous, tend to be much shorter-lived. In some instances, a spawner is a process that lives longer than spawn generated by that spawner. The spawn **22A**, **22B** are also independent of and asynchronous relative to each other so that the extent to which a spawn **22A**, **22B** has completed its computation is unrelated to when the spawner **20** generated that spawn **22A**, **22B** in the first place. As a result, the order in which spawn **22A**, **22B** carry out computations is indeterminate. Since the order in which computations are carried out can often affect the results, this makes the computation as a whole indeterminate.

During the course of its operation, the computing apparatus **8** communicates with the outside world. For example, the computing apparatus **8** may receive one or more streams of incoming messages **24** and produce one or more streams of outgoing messages **28**. As will be described in greater detail below, these messages **24**, **28** are

temporarily stored by the apparatus **8** within the durable storage **16**. These messages **24**, **28** may be temporarily stored for escrow within respective areas that are physically and/or logically separate. Incoming messages **24** can be stored in an incoming-message escrow area **26** in durable storage **16**, and outgoing messages **28** can be stored in an outgoing-message escrow area **30** in durable storage **16**.

Referring to FIG. 2, the node's operation is marked by checkpoint intervals **32** and working intervals **34**. During a working interval **34**, the node performs useful work as processes advance towards completion. During the checkpoint interval **32**, the node **10** suspends all processes, serializes them, and saves the result to durable storage **16**. The node **10** then saves anything else that is in working-memory into the durable storage **16**. At this point, the checkpoint is said to have been "committed" and the processes **14** are said to have been "checkpointed."

It is preferable that the checkpoint interval **32** be much shorter than the working interval **34**. The apparatus and methods described herein are intended to increase the amount of processing that can be performed in the working intervals **34** by reducing the length of the checkpoint interval **32**.

Once a checkpoint is committed, the node **10** allows processes **14** to resume and releases outgoing messages **28** that are in the outgoing-message escrow area **30**.

The storing of outgoing messages **28** in an outgoing-message escrow area **30**, rather than sending them immediately, is useful to guard against inconsistency that may result from a failure of the node **10**. For example, it would be quite possible for a process **14** to send an outgoing message **28** announcing the result of some computation. If the node **10** were to fail after this message **28** has already been sent but before the computational result is committed to durable storage **16**, the node **10** would re-start and re-execute the uncommitted computation. Upon completion, another message **28** would be sent announcing the result of this second computation. If the two results are different, which is not unlikely in the case of non-deterministic computations, one of the messages will be invalid.

As a concrete example, consider the case in which a process **14** awards a prize to a customer based on the result of a random number generator. Without the outgoing-message escrow area **30**, the process **14** would send a message **28** to a first

customer announcing that a prize was forthcoming. The node **10** would then crash and re-start. Since the state of the process **14** was never saved, there is no record of that customer having been awarded any prize, or of the process **14** having successfully completed execution. The node **10** may then re-execute the process **14**, which would then generate a different random number, thus causing a second message **28** to be sent to another customer announcing that a prize was forthcoming. This would require either awarding two prizes where only one was intended, or managing at least one disappointed customer.

To recover after a failure, the node **10** retrieves, from durable storage **16**, the state of all processes **14** and the state of working-memory **12**. It then retransmits any outgoing messages **28** that are stored in the outgoing-message escrow area **30**, retrieves incoming messages from incoming-message escrow area **16** for processing, and then resumes normal operation on live data.

The retransmission of all messages **28** in the outgoing-message escrow area **30** can result in recipients receiving duplicate messages. In one embodiment, the recipient is configured to ignore repeated messages **28**. In another embodiment, upon recovery, the recipient and the recovered node **10** communicate to identify messages **28** that have been received. This permits the node **10** to avoid sending duplicate messages **28**.

The procedure described above introduces results in a lengthy checkpoint interval **32**, which may, in turn, result in either low throughput or an increased latency between the receipt of an incoming message and the production of a corresponding outgoing message. A variety of methods can be used to reduce this latency, and/or increase the throughput.

A first optimization method features the maintenance of a journal **36** in the background. Every time an item in the working-memory **12** is altered a corresponding entry will be written to the journal **36** such that the journal entry may be used to reproduce the alteration at recovery time. The journal **36** may be asynchronously transferred to durable storage **16**. During the checkpoint interval **32** the node **10** will ensure that all journal entries have indeed been made durable. Recovery can then be

achieved by using an older checkpoint file **18** containing a snapshot of working-memory **12** and applying the changes as set forth in the journal **36**.

This optimization reduces the length of the checkpoint interval **32** but at the cost of increasing the time to recover. In particular, the longer it has been since the last full image of working-memory **12** was obtained, the greater the number of entries there will be in the journal **36**. This will increase recovery time.

A second optimization method relies on the fact that the node **10** has only a few spawning processes **20**, each of which generates (or "spawns") multitudes of short-lived processes, referred to herein in both the singular and plural as the "spawn **22A**, **22B**."

The lifetime of spawn **22A**, **22B** is random, but has an expected value that is much shorter than the expected value of the lifetime of a spawner **20**. As such, it makes little sense to spend time serializing spawn **22A**, **22B** during a checkpoint. In fact, in some cases, the time required to serialize spawn **22A**, **22B** is an appreciable fraction the spawn's expected lifetime. It is therefore often advantageous to instead suspend the spawner **20**, thus preventing generating of new spawn and to then allow the existing spawn **22A**, **22B** to terminate naturally.

To save time, the checkpoint-generating method, as shown in FIG. 3, includes suspending a spawner **20** (step **38**) and serializing it (step **40**). However, existing spawn **22A** continue executing (step **42**). Then, after a straggler's deadline, which is selected to define a sufficiently long idle-down interval be long enough to allow most spawn **22A** to finish executing but not so long as to appreciably impact latency (step **46**), spawn that are still executing, referred to as "straggling spawn," are suspended (step **48**), and serialized (step **50**).

The foregoing method thus reduces the length of the checkpoint interval **32** by reducing the number of processes **14** that need to be serialized. It does so by allowing processes **22** that are expected to terminate quickly to do so, thus eliminating the need to serialize those processes **22** as part of creating a valid checkpoint.

A third optimization procedure arises from the recognition that the evil to be avoided is actually a change to the working-memory **12** during the checkpoint interval

32. Therefore, if a process **14** does not actually have to write to working-memory **12**, but instead only has to read working-memory **12**, it makes no sense to suspend it.

To implement this third optimization procedure, the node **10** relies on a generation count associated with each process. Since the spawner **20** is a process, it has a generation count. Since the spawn **22A**, **22B** of a spawner is also a process, it too has a generation count. The generation counts of a spawn **22A** and a spawner **20** that spawned that spawn **22A** are related. In particular, the generation count of a spawn **22A**, **22B** is equal to the generation count of the spawner **20** that spawned it. The act of causing the generate count of a spawn **22A, 22B** to be related to, or derivable from, the generation count of the spawner that spawned it is described by the appropriate form of the verb "to inherit." When a spawner **20** with a particular generation count generates spawn **22A**, **22B**, the spawn **22A**, **22B** is said to have inherited the spawner's generation count.

In operation, prior to the onset of a checkpoint interval **32**, a spawner **20** will have generated older-generation spawn **22A**. At the beginning of the checkpoint interval **32**, the spawner **20** is "youthened."

The verb "to youthen" and its variants and cognates describes a particular computational operation that can be carried out on an integer. As used herein, the particular integer upon which the youthening operation operates is the generation count. describes an operation that can be carried out on a generation count.

In the particular example described herein, the act of youthening a spawner **20** means the act of incrementing its generation count. After having been youthened, the spawner **20** then continues to generate spawn during the checkpoint interval **32**, only now, it generates younger-generation spawn **22B**. The result of this is that two kinds of spawn **22** coexist within the node **10**: older-generation spawn **22A**, which the spawner **20** generated before having been youthened, and a younger-generation spawn **22B**, which the spawned **20** generated after having been youthened.

Referring to FIG. 4, at the beginning of a checkpoint interval, the spawner **20** is suspended (step **52**), such that it does not generate any new spawn while being suspended, and its process state saved (step **54**). The spawner **20** then has its generation count incremented (step **56**), after which the spawner **20** resumes (i.e., is

un-suspended). After resuming, the spawner **20** is once again able to generate spawn **22**, though this time, all its spawn **22B** will be in the younger-generation spawn.

Any younger-generation spawn **22B** that attempt to write to the working-memory **12**, are blocked until the checkpoint interval **32** is completed. Thus, younger-generation spawn **22** cannot run to completion. They can only run until it is time to actually write to working-memory **12** for the first time. Nevertheless, younger-generation spawn **22** can at least run partway to completion. This allows some processing to occur even during a checkpoint interval **32**.

In general, during the checkpoint interval **32**, all processes **14** in memory **12** will be serialized. However, in the optimization method of FIG. 4, it is desirable to serialize only older-generation spawn **22A**.

The generation count enables the node **10** to identify which spawn is younger-generation spawn **22B** and to therefore avoid saving their state.

Unfortunately, having to wait for older-generation spawn **22A** to complete processing tended to increase latency because younger-generation spawn **22B** could not proceed full bore until either all older-generation spawn **22A** were done or until the straggler deadline triggered suspension of stragglers from the older-generation spawn **22A**.

In a variant of the second optimization method, instead of blocking younger-generation spawn **22B** that attempt to modify working-memory **12**, and thus losing the opportunity to continue doing useful work, the node **10** can tag each data item in working-memory **12** with a generation number. If a younger-generation spawn **22B** modifies a memory location, rather than blocking until after the checkpoint, the node **10** will youthen the memory location by updating its generation number. Then, if an old-generation spawn **22A** attempts to read or write such a youthened memory location the older-generation spawn **22A** will spontaneously youthen itself by suspending itself, writing its state to the checkpoint, updating its generation number, and resuming execution in a youthened state. The node **10** also tags the entries written to the journal with the generation number so that it can distinguish journal entries corresponding to the older generation of spawn from journal entries corresponding to the younger generation of spawn.

A fourth optimization method relies on the idea of allowing younger-generation spawn **22B** to continue processing even past the first attempted write to working-memory **12**. This method relies on the fact that sometimes, the order in which computational results are written into working-memory **12** does not matter. If this is the case, writes to working-memory **12** can simply be queued until later. This method allows a younger-generation spawn **22B** to keep working during a checkpoint interval **32** even after the first time attempts to write to working-memory **12**.

In general, whenever one carries out a sequence of operations, a question that arises is whether or not the order of operations in the sequence makes a difference in the result of the sequence. An operation within this sequence is said to be "commutable" if the location of that operation within the sequence does not affect the result. Otherwise, the operation is "non-commutable." Examples of commutable operations are instructions to increment or decrement a value, instructions to insert a record into a list at some defined location, and in general, any operation that does not require reading a value to be carried out. The fourth optimization method exploits these commutable operations.

Referring now to FIG. 5, in this fourth optimization method, a node **10** receives a write request from a younger-generation spawn **22B** (step **60**) at a time when normally the younger-generation spawn **22B** would not be permitted to write to memory **12**. However, in this method, the node **10** distinguishes between commutable operations and non-commutable operations (step **62**). If the proposed write is commutable, the node **10** queues it (step **64**). The younger-generation spawn **22B** then continues execution (step **66**). This allows the younger-generation spawn **22B** to continue processing past the first time it tries to write to working-memory **12**. As a result, younger-generation spawn **22B** continue to execute during the checkpoint interval **32** for as long as any write operations carried out by that younger-generation spawn **22B** are commutable. On the other hand, if the proposed write is a non-commutable write, then the node **10** suspends execution of the younger-generation spawn **22B** (step **68**).

In addition to non-commutable writes, there may be other conditions in which a spawn **22B** may be allowed to write under conditions when it would normally not be able to do so. One other example arises when a younger-generation spawn **22B**, after

having inspected memory **12**, recognizes that no further memory access by an older-generation spawn **22A** is possible.

A fifth optimization method is one that reduces the latency that arises because the outgoing-message escrow area **30** does not release outgoing messages **28** until a checkpoint interval **32** is complete and all computations associated with generating the outgoing messages **28** have been committed to durable storage **16**. The idea of waiting until the end of a checkpoint interval **32** before releasing messages **28** from outgoing-message escrow area **30** is useful where the consequences of sending the wrong message are severe. However, there are times when the consequence of sending an incorrect message is minimal, but the consequence of sending a delayed message is severe.

As an example, consider the case in which the outgoing message **28** is a coupon for goods in a particular retail store. Suppose the apparatus has detected that a user is in the vicinity of that particular retail store at a particular instant. Obviously, it would be desirable to transmit the message **28** immediately, before the user has had a chance to leave the retail store. If this message **28** were to languish on the outgoing-message escrow area **30** waiting to be sent, the opportunity for the coupon to be useful would be lost. On the other hand, if that coupon were the result of a computation that was subsequently lost because of a failure in the node **10**, it is unlikely anybody would complain. After all, the store would have made a sale it might not otherwise have made, and the user would have obtained a good at some discount.

This fifth optimization method, in which outgoing messages **28** are released without waiting for the underlying data to be committed to durable storage **16**, presupposes that time is of the essence in delivering an outgoing message **28**, and that the cost of an incorrect or inconsistent outgoing message **28** is minimal in comparison with adverse consequences of its late delivery. In the fifth optimization method, outgoing messages **28** are released from the outgoing-message escrow area **30** prior to completion of the checkpoint interval **32** or bypass the outgoing-message escrow area **30** completely.

FIG. 6 shows a multi-node apparatus **70** in which multiple nodes **72**, **74**, **76**, **78** of the type described in connection with FIGS. 1-6 are in communication with

each other and cooperate with each other in carrying out data processing. In such a case, a task may send a message from a first node **72** to a second node **74**.

In some cases the message may have the effect of migrating a task from the first node **72** to the second node **74**. A task that migrates from one node to another is referred to as a "migrant" task. Depending on point-of-view, a migrant task is either an "immigrant" task or an "emigrant" task. From the point of view of the first node **72**, the migrant task is an "emigrant" task because the task is leaving the first node. Conversely, from the point of view of the second node **74**, the migrant task is an "immigrant" task because it is arriving at the second node **74**.

In other cases the message might be a remote procedure call or a remote data access request such that the requesting task cannot proceed until it receives a message in return. In other cases the task may simply asynchronously transmit information from the first node **72** to the second node **74** using the message. A computing system such as that described in U.S. Patent Application Serial No. 14/842,956, entitled "EXECUTING GRAPH-BASED PROGRAM SPECIFICATIONS," filed on September 2, 2015, incorporated herein by reference, for example, can be configured using the techniques for promoting fault tolerance and recovery described herein.

In such a case, application of the foregoing methods would be less than optimal in part because a message **80** from the first node **72** to the second node **76** cannot be transmitted until it is released from escrow at the completion of the next checkpoint interval **32**. This introduces considerable latency. While this latency could potentially be reduced by exempting messages transmitted from node to node within the multi-node apparatus **70** from being escrowed, such an exemption is not sufficient due to indeterminism.

For example, this and other difficulties arise when multiple nodes **72**, **74**, **76**, **78** are present because many computations are non-deterministic. Examples of such non-deterministic computations are those in which results depend on the order in which reads and writes occur, those that rely on real time clocks, and those that rely on the outcome of a random number generator, an example of which has already been described above in connection with the desirability of an outgoing-message escrow area **30**.

If a first node **72** communicates with a second node **74**, then loses contact (e.g., due to failure) before the next checkpoint interval **32**, the apparatus **70** may end up with inconsistencies owing to this non-determinism as follows. After the failure the apparatus **70** will recover the first node **72** from the most recent checkpoint and restart the computation. The computation may be restarted from a point in the computation before transmission of a message from the first node **72** to the second node **74**. Owing to the non-deterministic nature of the computations, the first node **72** may well send a completely different message to the second node **74** after recovery from the checkpoint. But, that second node **74** may have already received the original message, potentially placing the two nodes **72** and **74** in an inconsistent state. For example, node **72** is in a state in which it has sent node **74** the "new" version of the message, but node **74** is in a state in which it has already acted on the "old" version of the message. Furthermore, node **74** may have sent a message to yet another node **76**, based on that original message received from node **72**, so node **72** and node **76** are also may also be in an inconsistent state. Thus, inconsistency may spread through all nodes in the apparatus **70** like a virus.

One way to avoid the foregoing difficulty is to ensure that all the nodes **72**, **74**, **76**, **78** synchronize their checkpoints, for example, using a 'barrier sync' operation, as follows. A 'checkpoint leader' transmits a message to all nodes commanding them to begin a checkpoint interval. Then, after each checkpoint is complete, each node responds to the checkpoint leader affirming that the checkpoint is complete. When the checkpoint leader has received affirmations from all nodes, it will then command all nodes to commit the checkpoint and then resume processing.

This approach forms the basis of a solution to the multi-node checkpoint problem, but does not completely solve it for two reasons. First, in a multi-node apparatus it is possible that some nodes survive a failure, in which case the surviving nodes must be rolled back from their current state to the checkpoint state (rather than being rolled forward to the checkpoint state). Second, when the checkpoint is performed there may be messages in transit, which might allow non-determinism to leak from the old processing interval, across the checkpoint, and into the new processing interval.

In a single-node apparatus, if the node **10** fails, it only has to roll forward to recover uncommitted work. But in a multi-node apparatus **70**, other nodes **72**, **74**, **76**, which did not fail, may have to roll backward when a node **78** fails. This mechanism, in which a distributed apparatus **70** recovers by having some nodes **78** roll forward and other nodes **72**, **74**, **76** roll backward means that in effect, all nodes **72**, **74**, **76**, **78** can be made to restart at the same checkpoint. The resulting apparatus **70** thus achieves the effect of simultaneous checkpoints across all nodes. It does not, however, do so by trying to actually synchronize operation across all nodes, which as noted above is difficult. Instead, it does so by manipulating the states of the nodes **72**, **74**, **76**, **78** to reap the benefits of synchronized checkpoints without actually having to provide such checkpoints.

To implement the foregoing recovery method, the nodes **72**, **74**, **76**, **78** execute a distributed checkpoint method as described in detail below. Referring to FIG. 7, when implementing the distributed checkpoint method, every process and every message acquires a generation count **82**. In addition, a running count **84** is maintained of the tasks associated with each checkpoint. Each node also maintains a spawner-registry **86** of its spawners **20**. Additionally, each node **72** maintains a nodal generation count **88**.

The nodal generation count **88** enables a node **76** to enforce a generation gap in which work carried out by younger-generation spawn **22A** and work carried out by older-generation spawn **22B** do not interfere with each other. As a result of the generation gap, the older generation and the younger generation can more or less ignore each other. In effect, the node **76** becomes two virtual machines, one seen by the older-generation spawn **22A** and another seen by the younger-generation spawn **22B**. These two virtual machines coexist on the same physical platform but are otherwise orthogonal to each other.

In addition, each node **76** also implements a bidirectional journal **90** that enables that node **76** to roll forward or backward to a particular state as needed. The bidirectional journal **90** includes changes to working storage **92**, a listing of checkpointed task states **94**, and checkpointed messages **96**. These elements provide a way to roll forward in time. In addition, the bidirectional journal **90** features an undo log **98** in memory **12** to enable the node **76** to roll backward in time. In general,

rolling forward in time is how a failed node recovers. Rolling backward in time is what a node does when another node in the apparatus **70** has failed.

In operation, as shown in FIG. 6, a master node **72** transmits a checkpoint message **100** to all other nodes **74**, **76**, **78**, i.e. "slave nodes," indicating that a checkpoint is due. However, there is no requirement that this checkpoint occur at the same time in all nodes **72**, **74**, **76**, **78**.

FIG. 8 shows a flowchart for an exemplary fault-tolerance and recovery procedure in the presence of computational indeterminism. In response to receiving a checkpoint message (step **102**), a slave node **76** will not immediately begin a checkpoint interval. As noted above, this is impractical. Instead, the slave node **76** increments its nodal generation count **88** (step **104**) and create a journal entry indicating the incrementing of its nodal generation count **88** (step **106**).

The slave node **76** then suspends all of its spawners **20** (step **108**), and writes their states to the bidirectional journal **90** (step **110**). Then, for each of its spawners **20**, the slave node **76** increments that spawner's generation count **82** (step **112**). With its generation count **82** having been incremented, the spawner **20** is allowed to resume operation (step **114**). However, since the spawner's generation count **82** will have been incremented, any resulting spawn **22B** will be in the younger generation.

At this point, two generations will co-exist in the slave node **76**. The older-generation spawn **22A**, namely those having a generation count that is one less than the node's generation count, can continue to process to completion, writing to memory **12** as necessary. The younger-generation spawn **22B**, namely those whose generation counts match the nodal generation count **88**, may process until it is time to write to memory **12**. At that point, younger generation spawn **22B** are blocked.

It should be noted that in the description thus far, there are only two generations of spawn involved: older-generation spawn **22A**, whose generation count **82** is one less than the nodal generation count **88**, and a younger-generation spawn **22B**, whose generation count **82** matches the nodal generation count **88**. However, in principle there is no reason that more than two generations cannot coexist on the same platform.

Referring to FIG. 9, in a multi-node apparatus **70**, it is possible for a task **79** to emigrate from a sending node **78** and immigrate into a receiving node **76**. As described in connection with FIG. 6, such a task **79** is referred to as a "migrant task" or a "migrant."

In the following discussion, it is necessary to refer to values associated with particular objects. To avoid ambiguity with reference numerals in the figures, and in a manner consistent with standard mathematical notation, the parentheses will be used to mean "of." Thus, since "**88**" has been assigned to "nodal generation count" and "**76**" is a node, the nodal generation count **88** of node **76** will be written as **88(76)**.

A difficulty can arise when the migrant's generation count **82(79)** is not the same as the nodal generation count **88(76)** of the receiving node **76**. These difficulties can be avoided by implementing message escrow areas between nodes. But this would reintroduce the latency that the distributed checkpoint method was intended to avoid in the first place.

According to the distributed checkpoint method, there are three possibilities: the sending node's nodal count **88(78)** is the same as the receiving node's nodal count **88(76)**; the sending node **78** has a lower nodal generation count **88(78)** than the receiving node's nodal count **88(76)**; and the sending node **78** has a higher nodal generation count **88(78)** than the receiving node's **88(76)**.

In the first possibility, a migrant will have the same generation count **82(79)** as the nodal count **88(78)** of the sending node **78**. Therefore, the sending node **78**, the receiving node **76**, and the migrant **79** all have the same generation count. In that case, nothing special has to be done.

The second possibility can arise when the receiving node **76** increments its generation count **88(76)** while the migrant **79** is in transit. This means that, upon immigrating into the receiving node **76**, the migrant **79** presents itself as a member of what has now become the older generation of the receiving node **76**. In that case, the receiving node **76** will youthen the migrant **79** by incrementing the migrant's generation count **82(79)**. As a result, the migrant task **79** will be able to continue processing, but, like the rest of the younger generation spawn **22B**, it will be blocked from writing to memory **12**. The youthening of the migrant **79** is then journalized at

the receiving node **76**. Since the act of youthening takes place at the receiving node **76**, it is referred to as "immigrant-side youthening."

The third possibility can arise when the sending node **78** will increment its generation count **88(78)** before the migrant **79** has emigrated. In that case, the sending node **78** youthens the migrant **79** by incrementing the migrant's generation count **82(79)** before it is sent, and journalizes the youthening event at the sending node. Since the act of youthening takes place at the sending node **78**, it is referred to as "emigrant-side youthening."

In either case, a node **76** that has received a checkpoint message from a master node will set a deadline to allow the older-generation spawn **22A** to finish execution, thereby insuring near-extinction of the older generation, and avoiding the need to record their states (step **116**). Nevertheless, there may be spawn **22A** of the older generation that are slow to terminate. It is impractical for a node **76** to wait for an extended period for once the deadline is reached, any older generation spawn **22** that is still running will be suspended, serialized, journaled, and youthened, after which it is allowed to resume execution subject to the constraint that it not write to the working-memory **12** until after the working-memory **12** has been committed to durable storage **16**.

The slave node **76** will not begin the actual checkpoint until it knows that no more older-generation immigrants are expected to arrive. In order to implement this, whenever a node **72** recognizes that all older-generation emigrants have successfully emigrated, it broadcasts a flush message to all other nodes **74**, **76**, **78**. Once the slave node **76** has received flush messages from all nodes **72**, **74**, **78**, it knows that the flow of older-generation immigrants has been quenched (step **118**). Younger-generation immigrants may still arrive at a slave node **76**, just as younger-generation emigrants may still leave from the slave node **76**. However, these younger-generation emigrants are not pertinent to the checkpoint process.

At this point, the slave node **76** is now ready to commit its working-memory **12** to durable storage **16** (step **120**). This is carried out in the same manner described above for the single-node case.

The procedure for restarting after failure of a node, shown in FIG. 10, depends on whether the node involved is one that failed or not. After receiving an instruction to restart (step **122**), the node determines if it is the node that failed, or if another node in the apparatus **70** failed (step **124**). If the node is one that failed, it retrieves the log and rolls forward from its last valid checkpoint (step **126**). If the node is not one that failed (i, it rolls back to its last checkpoint (step **128**).

An example of a "roll back" operation involves the following steps: (1) terminate all tasks currently running (including both spawners and spawn); (2) use the bidirectional journal entries to undo any changes to memory.

After any failed nodes have been rolled forward and any surviving nodes have been rolled back, the apparatus **70** may also perform other operations as part of restarting the tasks. For example, the apparatus **70** may perform the following operations: (1) flush the communications network to ensure that all messages predating the failure have been discarded, (2) restart all tasks that were part of the checkpoint by retrieving their saved state from the journal and restarting them, (3) retransmit any messages that were not sent prior to the checkpoint, and (4) process any messages were received but not yet processed as of the checkpoint.

The task of rolling forward from the last valid checkpoint on a failed node is one that is potentially time-consuming. Referring to FIG. 11, in some practices, it is useful to maintain a replica **128** of memory **130** from a first node **132** on a second node **134**. Preferably, the second node **134** does not have the same failure mode as the first node **132**. In normal operation, the replica **128** is synchronized with the memory **130** at the first node **132** at each checkpoint. The replica **128** also has an associated undo log **136** to enable it to roll backward to its state at the most recent checkpoint.

Referring now to FIG. 12, upon failure of the first node **132**, the replica **128** at the second node **124** is designated a master (step **138**). All processes on the second node **124** are killed (step **140**), after which the second node **134** is restarted (step **142**). The former replica **128**, which now serves as a master copy, is rolled back to the last checkpoint with the aid of the undo log **136** (step **144**). Operation of the multi-node apparatus **70** can then resume with the wait for recovery being on the order of the roll-back time. This is typically much shorter than the roll-forward time. Meanwhile, the

recovered first node **132** can proceed to roll-forward to the correct state without slowing down the overall recovery of the multi-node apparatus **70**. Once the first node **132** is ready, it takes over as master again, and the former replica **128** becomes a replica again.

Although FIG. 11 shows only one second node **134**, it is understood that there can be more than one second node, each of which has a replica **128** and an undo log **136**. In that case, upon failure of the first node **132**, one of the second nodes must be elected to serve as proprietor of the new master copy of the first node's memory.

In some cases, there may be many idempotent operations. In such cases, instead of rolling forward it is not unreasonable to simply repeat computations that would carry out idempotent operations since those computations would not cause any harm.

The end result of recovery is that all points are at a state consistent with the transition from one generation to the next. As a result, no work from older-generation processes is lost, but all work done by younger generation processes is lost. This ensures a state that is consistent across all nodes. In this context, a state is "consistent" if it could have been arrived at in the absence of any fault. In contrast, a state is "inconsistent" if it can only be explained by the occurrence of one or more faults.

FIG. 13 illustrates the states of several spawned processes in both the sending node **78** and receiving node **76** in the multi-node apparatus **70** referred to in connection with FIGS. 6 and 9. In FIG. 13, time increases downward along the vertical axis. The time axis shows a first interval **146**, a second interval **148** following the first interval **146**, and a third interval **150** following the second interval **148**.

FIG. 13 shows several spawned processes **22A-H**, each of which has an associated generation count. Spawn having a generation count of N will be referred to herein as "first-generation spawn." Spawn having a generation count of N+1 will be referred to herein as "second-generation spawn." The adjectives "first-generation" and "second-generation" will also be used to refer to other entities that are tagged with a generation count, including nodes, migrant tasks, and spawned process.

During the first interval **146**, the sending node **78** is a first-generation node. During the second and third interval **150**, the sending node **78** is a second-generation node. It should be noted that this progression of nodes is cyclic so that the third interval **150** will be followed by an interval that plays the same role, for the second generation, that the second interval **148** played for the first generation. This same progression occurs on the receiving node **76**, though not necessarily in synchrony with the progression occurring at the sending node **78**. For convenience, the same reference numbers are used to designate intervals in both the sending and receiving nodes **78**, **76**. However, this is not meant to imply that they are synchronized.

During the first interval **146**, a spawning process **20** spawns various first-generation spawned processes **22A-22E**. Throughout this first interval **146**, any first-generation spawned process **22A-22E** is free to write to a sending-node memory **12A**.

During the second interval **148**, the sending node **78** becomes a second-generation node. As such, the spawning process **20** now spawns only second-generation spawned processes. During this second interval **148**, any first-generation spawned processes **22A-22E** remain free to write to the sending-node memory **12A**. Second-generation spawned processes **22F-22G** are free to execute, but are forbidden from writing to the sending-node memory **12A**. The purpose of this second interval **148** is therefore to allow any residual first-generation spawn **22C, 22D, 22E** some time to finish executing before a checkpoint interval **32** occurs.

During the third interval **150**, the spawning process **20** spawns another second-generation spawned process **22H**. During this third interval **150**, no first-generation spawn remain, and all second-generation spawn **22F-22H** are free to write to the sending-node memory **12A**.

At the sending node **78**, a first first-generation spawned process **22A**, a second first-generation spawned process **22B**, a third first-generation spawned process **22C**, a fourth first-generation spawned process **22D**, and a fifth first-generation spawned process **22E** all begin execution during the first interval **146**. However, of these, only the first first-generation spawned process **22A** and the second first-generation spawned process **22B** manage to finish execution during the first interval **146**. The third first-generation spawned process **22C** manages to finish during the second

interval **148**. The fourth first-generation spawned process **22D** takes so long it cannot finish until the third interval **150** has already begun. The fifth first-generation spawned process **22E** never actually finishes at the sending node **78**. Instead, it migrates to the receiving node **76** part way through the second interval **148**. It does so while the receiving node **76** is still in its own second interval **148**.

During execution, the first first-generation spawned process **22A** writes to the sending-node memory **12A** during the first interval **146** and the third first-generation spawned process **22C** writes to the sending-node memory **12A** during the second interval **148**. The second first-generation spawned process **22B** does not write to the sending-node memory **12A** at all during execution. The fifth first-generation spawned process **22E** eventually writes to the sending-node memory **12A**, but only at the receiving node **76**.

During the second interval **148**, a first second-generation spawned process **22F** and a second second-generation spawned process **22G** both begin execution. Sometime during the second interval **148**, the first second-generation spawned process **22F** reaches a point at which it must write to the sending-node memory **12A**. However, since it is still the second interval **148**, it is forbidden from writing to the sending-node memory **12A**. Therefore, it becomes suspended, as indicated by the dashed lines. Once the third interval **150** begins, the first second-generation spawned process **22F** writes to the sending-node memory **12A** and completes execution.

Meanwhile, the second second-generation spawned process **22G** has started late enough during the second interval **148** so that by the time it actually has to write to the sending-node memory **12A**, the third interval **150** has already begun. Accordingly, the second second-generation spawned process **22G** executes without interruption.

A third second-generation spawned process **22H** begins during the third interval **150**. This is essentially a mirror image of the first first-generation spawned process **22A**.

In the course of execution, the first first-generation spawned process **22A** causes a first task **152** to migrate to the receiving node **76**. The first task **152** inherits the generation number of the first first-generation spawned process **22A**. As such, it

begins its existence as a first-generation task. This first task **152** arrives at the receiving node **76** while the receiving node **76** is still operating in the first interval **146**. The receiving node **76** is thus acting as a first-generation node. Accordingly, the first task **152** is free to execute and to write to a receiving-node memory **12B** provided it does so before a third interval **150** begins on the receiving node **76**.

Also in the course of execution, the second first-generation spawned process **22B** causes a second task **154** to migrate to the receiving node **76**. The second task **154** inherits the generation number of the first first-generation spawned process **22A**. As such, it starts its existence as a first-generation task. However, this second task **154** arrives at the receiving node **76** while the receiving node **76** is already operating in its second interval **148**. Accordingly, the second task **154** is changed into a second-generation task from a first-generation task. This includes an accompanying step of journalizing the second task **154** in a receiving node journal file **156**.

A similar event occurs in connection with the fifth first-generation spawned process **22E** at the sending node **78**. This fifth first-generation spawned process **22E** migrates to the receiving node **76** midway through execution. However, by the time it arrives at the receiving node **76**, the receiving node **76** has already begun its own second interval **148**. As such, the second node is has become a second-generation node. Therefore, the fifth first-generation spawned process **22E** is changed into a second-generation spawned process. This change is accompanied by journalizing the fifth first-generation spawned process **22E** in a sending-node journal file **158**. The fifth first-generation spawned process **22E** then continues execution on the receiving node **76**, though as a second-generation spawned process.

Meanwhile, back at the sending node **78**, the fourth first-generation spawned process **22D** has not yet finished execution by the end of the second interval **148**. At this point, the fourth first-generation spawned process **22D** is both journalized at the sending-node journal file **158** and has its generation count incremented so that it now becomes a second-generation spawned process. The fourth first-generation spawned process **22D** then continues to execute during the third interval **150**.

It should be noted that the fourth first-generation spawned process **22D** sustained the same two steps that were sustained by the fifth first-generation spawned

process **22E** during its migration to the receiving node **76**, namely a journalizing step, and a generation change. Thus, it is not unreasonable to say that fourth first-generation spawned process **22D** in some sense also migrated. The main difference is that the fifth first-generation spawned process **22E** underwent an inter-node migration whereas the fourth first-generation spawned process **22D** underwent an intra-node migration.

The checkpoint and recovery method described herein is thus based on the recognition that the desirability of simultaneously executing checkpoints across multiple nodes does not stem from temporal synchronicity but rather from a side effect of temporal synchronicity. The method thus reproduces the side effect of temporal synchronicity of checkpoints across multiple nodes without actually having to achieve it.

The fault-tolerance and recovery approach described above can be implemented, for example, using a programmable computing system executing suitable software instructions or it can be implemented in suitable hardware such as a field-programmable gate array (FPGA) or in some hybrid form. For example, in a programmed approach the software may include procedures in one or more computer programs that execute on one or more programmed or programmable computing system (which may be of various architectures such as distributed, client/server, or grid) each including at least one processor, at least one data storage system (including volatile and/or non-volatile memory and/or storage elements), at least one user interface (for receiving input using at least one input device or port, and for providing output using at least one output device or port). The software may include one or more modules of a larger program, for example, that provides services related to the design, configuration, and execution of dataflow graphs. The modules of the program (e.g., elements of a dataflow graph) can be implemented as data structures or other organized data conforming to a data model stored in a data repository.

The software may be stored in non-transitory form, such as being embodied in a volatile or non-volatile storage medium, or any other non-transitory medium, using a physical property of the medium (e.g., surface pits and lands, magnetic domains, or electrical charge) for a period of time (e.g., the time between refresh periods of a dynamic memory device such as a dynamic RAM). In preparation for loading the

instructions, the software may be provided on a tangible, non-transitory medium, such as a CD-ROM or other computer-readable medium (e.g., readable by a general or special purpose computing system or device), or may be delivered (e.g., encoded in a propagated signal) over a communication medium of a network to a tangible, non-transitory medium of a computing system where it is executed. Some or all of the processing may be performed on a special purpose computer, or using special-purpose hardware, such as coprocessors or field-programmable gate arrays (FPGAs) or dedicated, application-specific integrated circuits (ASICs). The processing may be implemented in a distributed manner in which different parts of the computation specified by the software are performed by different computing elements. Each such computer program is preferably stored on or downloaded to a computer-readable storage medium (e.g., solid state memory or media, or magnetic or optical media) of a storage device accessible by a general or special purpose programmable computer, for configuring and operating the computer when the storage device medium is read by the computer to perform the processing described herein. The inventive system may also be considered to be implemented as a tangible, non-transitory medium, configured with a computer program, where the medium so configured causes a computer to operate in a specific and predefined manner to perform one or more of the processing steps described herein.

A number of embodiments of the invention have been described. Nevertheless, it is to be understood that the foregoing description is intended to illustrate and not to limit the scope of the invention, which is defined by the scope of the following claims. Accordingly, other embodiments are also within the scope of the following claims. For example, various modifications may be made without departing from the scope of the invention. Additionally, some of the steps described above may be order independent, and thus can be performed in an order different from that described.

Having described the invention, what we claim as new, and secured by letters patent is:

CLAIMS

1. A method for enhancing fault tolerance and recovery in a computing system including at least one processing node, said method including:

enhancing availability and recovery of a first processing node, including, at the first processing node,

executing a spawner at said node, wherein said spawner, in the course of execution, generates a first spawn, wherein the spawner implements a process, with an associated expected spawner lifetime, configured to generate one or more spawn processes, including the first spawn, that are each associated with a respective expected lifetime shorter than the expected spawner lifetime, and which are configured to be suspended if, following a checkpoint event and suspension of the spawner, the respective one or more spawn processes are still executing after a pre-determined interval measured from occurrence of the checkpoint event and suspension of the spawner, wherein at least one of the one or more spawn processes terminates before the end of the pre-determined interval,

wherein executing said spawner includes assigning, to said spawner, a first generation indicator,

wherein said first spawn inherits said first generation indicator;

beginning a checkpoint interval, at the end of which nodal recovery information, which is usable for recovery of said node, is committed to durable storage, wherein beginning said checkpoint interval includes

suspending said spawner from generating spawn,

assigning, to said spawner, a second generation indicator that differs from said first generation indicator,

resuming said spawner, thereby enabling said spawner to generate a second spawn, wherein said second spawn inherits said second generation indicator, and

controlling an extent to which said second spawn writes to memory; and

after committing said nodal recovery information, releasing control over said extent to which said second spawn can write to memory.

2. The method of claim **1**, wherein controlling an extent to which said second spawn writes to memory includes preventing said second spawn from consummating a write to said memory.

3. The method of claim **2**, further including permitting said second spawn to queue said write to memory for eventual consummation thereof after said recovery information has been committed.

4. The method of claim **1**, wherein controlling an extent to which said second spawn writes to memory includes determining that said write operation is a commutable operation whose sequence with respect to other operations does not affect a result of said commutable operation, and allowing consummation of said commutable operation.

5. The method of claim **4**, wherein determining that said write operation is a commutable operation includes determining that said write operation includes incrementing a variable.

6. The method of claim **4**, wherein determining that said write operation is a commutable operation includes determining that said write operation includes inserting a record at a specified location.

7. The method of claim **1**, further including, after suspending said spawner, setting a deadline, thereby providing time for any spawn having said first task generation-indicator to execute to completion, and avoiding overhead associated with having to save states of said spawn having said first generation-indicator.

8. The method of claim **7**, further including suspending said first spawn if said first spawn is still executing as of said deadline.

9. The method of claim **7**, further including enabling said first spawn to avoid suspension as a result of having failed to complete execution by said deadline.

10. The method of claim **9**, wherein enabling said first spawn to avoid suspension as a result of having failed to complete execution by said deadline includes changing said first task generation-indicator to said second task generation-indicator in said first spawn if said first spawn is still executing as of said deadline.

11. The method of claim **1**, wherein said first node has a nodal-generation indicator, said method further including causing a spawn to become a migrant that migrates to a second node, wherein said second node has a nodal-generation indicator.

12. The method of claim **11**, wherein said nodal-generation counter of said second node indicates that said second node is in a younger generation than said first node, wherein said method further includes youthening said migrant to cause a generation indicator value of the migrant to be changed to indicate a younger generation value associated with the migrant.

13. The method of claim **12**, wherein youthening said migrant includes immigration-side youthening of said migrant.

14. The method of claim **12**, wherein youthening said migrant includes emigration-side youthening of said migrant.

15. The method of claim **1**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, wherein said multi-node system includes at least a second node, wherein, upon recovery following a failure of said second node, said first node rolls back to a state that corresponds to a nodal-generation count of said second node.

16. The method of claim **1**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, wherein said multi-node system includes at least a second node, wherein, upon recovery following a failure of said first node, said first node rolls forward to a state that corresponds to a nodal-generation count of said second node by restoring committed work from a checkpoint and restoring uncommitted work from a journal.

17. The method of claim **1**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, said method including, at said first node,

receiving, from a master node, a message indicating that a checkpoint is to be carried out,

in response, youthening a nodal generation count of said first node to cause the nodal-generation count of said first node be changed to indicate a younger generation value associated with the first node,

suspending spawners from generating spawn,

saving spawner recovery information for recovering spawner states,

resuming said spawners,

determining that no further older-generation immigrants are expected at said first node, and

in response to said determination, committing, to said durable storage, said nodal recovery information.

18. The method of claim **17**, further including setting a deadline, and, upon lapse of said deadline, suspending all older-generation spawn that are still executing while younger-generation spawn continue to execute.

19. The method of claim **1**, wherein said first node is a node in a multi-node system, said method including saving a replica copy of working memory of said first node at said second node, upon failure of said first

node, temporarily using said replica copy for processing that would otherwise have been carried out by said first node, and, upon recovery of said first node, communicating, to said first node, information required to update memory in said first node so that subsequent computation can be carried out by said first node.

20. A computer-readable storage medium having recorded thereon instructions for enhancing fault tolerance and recovery in a computing system including at least one processing node, the instructions being executable by a computing system to:

enhance availability and recovery of a first processing node, including, at a first processing node,

executing a spawner at said node, wherein said spawner, in the course of execution, generates a first spawn, wherein the spawner implements a process, with an associated expected spawner lifetime, configured to generate one or more spawn processes, including the first spawn, that are each associated with a respective expected lifetime shorter than the expected spawner lifetime, and which are configured to be suspended if, following a checkpoint event and suspension of the spawner, the respective one or more spawn processes are still executing after a pre-determined interval measured from occurrence of the checkpoint event and suspension of the spawner, wherein at least one of the one or more spawn processes terminates before the end of the pre-determined interval,

wherein executing said spawner includes assigning, to said spawner, a first generation indicator,

wherein said first spawn inherits said first generation indicator;

beginning a checkpoint interval, at the end of which nodal recovery information, which is usable for recovery of said node, is committed to durable storage, wherein beginning said checkpoint interval includes

suspending said spawner from generating spawn,

assigning, to said spawner, a second generation indicator that differs from said first generation indicator,

resuming said spawner, thereby enabling said spawner to generate a second spawn, wherein said second spawn inherits said second generation indicator, and

controlling an extent to which said second spawn writes to memory; and

after committing said nodal recovery information, releasing control over said extent to which said second spawn can write to memory.

21. The computer-readable storage medium of claim **20**, wherein controlling an extent to which said second spawn writes to memory includes preventing said second spawn from consummating a write to said memory.

22. The computer-readable storage medium of claim **21**, further including instructions for causing the computing system to permit said second spawn to queue said write to memory for eventual consummation thereof after said recovery information has been committed.

23. The computer-readable storage medium of claim **20**, wherein controlling an extent to which said second spawn writes to memory includes determining that said write operation is a commutable operation whose sequence with respect to other operations does not affect a result of said commutable operation, and allowing consummation of said commutable operation.

24. The computer-readable storage medium of claim **23**, wherein determining that said write operation is a commutable operation includes determining that said write operation includes incrementing a variable.

25. The computer-readable storage medium of claim **23**, wherein determining that said write operation is a commutable operation

includes determining that said write operation includes inserting a record at a specified location.

26. The computer-readable storage medium of claim **20**, further including instructions for causing the computing system to, after suspending said spawner, set a deadline, thereby providing time for any spawn having said first task generation-indicator to execute to completion, and avoiding overhead associated with having to save states of said spawn having said first generation-indicator.

27. The computer-readable storage medium of claim **26**, further including instructions for causing the computing system to suspend said first spawn if said first spawn is still executing as of said deadline.

28. The computer-readable storage medium of claim **26**, further including instructions for causing the computing system to enable said first spawn to avoid suspension as a result of having failed to complete execution by said deadline.

29. The computer-readable storage medium of claim **28**, wherein enabling said first spawn to avoid suspension as a result of having failed to complete execution by said deadline includes changing said first task generation-indicator to said second task generation-indicator in said first spawn if said first spawn is still executing as of said deadline.

30. The computer-readable storage medium of claim **20**, wherein the first node has a nodal-generation indicator, said computer-readable storage medium further including instructions for causing the computing system to cause a spawn to become a migrant that migrates to a second node, wherein said second node has a nodal-generation indicator.

31. The computer-readable storage medium of claim **30**, wherein said nodal-generation counter of said second node indicates that said second node is in a younger generation than said first node, wherein said computer-readable storage medium further includes instructions for causing the computing system to youthen said migrant to cause a

generation indicator value of the migrant to be changed to indicate a younger generation value associated with the migrant.

32. The computer-readable storage medium of claim **31**, wherein youthening said migrant includes immigration-side youthening of said migrant.

33. The computer-readable storage medium of claim **31**, wherein youthening said migrant includes emigration-side youthening of said migrant.

34. The computer-readable storage medium of claim **20**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, wherein said multi-node system includes at least a second node, wherein, upon recovery following a failure of said second node, said first node rolls back to a state that corresponds to a nodal-generation count of said second node.

35. The computer-readable storage medium of claim **20**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, wherein said multi-node system includes at least a second node, wherein, upon recovery following a failure of said first node, said first node rolls forward to a state that corresponds to a nodal-generation count of said second node by restoring committed work from a checkpoint and restoring uncommitted work from a journal.

36. The computer-readable storage medium of claim **20**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, said computer-readable storage medium including instructions for causing the computing system to, at said first node,

receive, from a master node, a message indicating that a checkpoint is to be carried out,

in response, youthen a nodal generation count of said first node to cause the nodal-generation count of said first node be changed to indicate a younger generation value associated with the first node,

suspend spawners from generating spawn,

save spawner recovery information for recovering spawner states,

resume said spawners,

determine that no further older-generation immigrants are expected at said first node, and

in response to said determination, commit, to said durable storage, said nodal recovery information.

37. The computer-readable storage medium of claim **36**, further including instructions for causing the computing system to set a deadline, and, upon lapse of said deadline, suspend all older-generation spawn that are still executing while younger-generation spawn continue to execute.

38. The computer-readable storage medium of claim **20**, wherein said first node is a node in a multi-node system, said computer-readable storage medium including instructions for causing the computing system to save a replica copy of working memory of said first node at said second node, upon failure of said first node, temporarily using said replica copy for processing that would otherwise have been carried out by said first node, and, upon recovery of said first node, communicate, to said first node, information required to update memory in said first node so that subsequent computation can be carried out by said first node.

39. A computing system including:

a data storage system including durable storage; and

one or more processing nodes including least one processor configured to enhance availability and recovery of a first processing node, including, at the first processing node,

executing a spawner at said node, wherein said spawner, in the course of execution, generates a first spawn, wherein the spawner implements a

process, with an associated expected spawner lifetime, configured to generate one or more spawn processes, including the first spawn, that are each associated with a respective expected lifetime shorter than the expected spawner lifetime, and which are configured to be suspended if, following a checkpoint event and suspension of the spawner, the respective one or more spawn processes are still executing after a pre-determined interval measured from occurrence of the checkpoint event and suspension of the spawner, wherein at least one of the one or more spawn processes terminates before the end of the pre-determined interval,

wherein executing said spawner includes assigning, to said spawner, a first generation indicator,

wherein said first spawn inherits said first generation indicator;

beginning a checkpoint interval, at the end of which nodal recovery information, which is usable for recovery of said node, is committed to durable storage, wherein beginning said checkpoint interval includes

suspending said spawner from generating spawn,

assigning, to said spawner, a second generation indicator that differs from said first generation indicator,

resuming said spawner, thereby enabling said spawner to generate a second spawn, wherein said second spawn inherits said second generation indicator, and

controlling an extent to which said second spawn writes to memory; and

after committing said nodal recovery information, releasing control over said extent to which said second spawn can write to memory.

40. The computing system of claim **39**, wherein controlling an extent to which said second spawn writes to memory includes preventing said second spawn from consummating a write to said memory.

41. The computing system of claim **40**, said processor further configured to permit said second spawn to queue said write to memory for eventual consummation thereof after said recovery information has been committed.

42. The computing system of claim **39**, wherein controlling an extent to which said second spawn writes to memory includes determining that said write operation is a commutable operation sequence with respect to other operations does not affect a result of said commutable operation, and allowing consummation of said commutable operation.

43. The computing system of claim **42**, wherein determining that said write operation is a commutable operation includes determining that said write operation includes incrementing a variable.

44. The computing system of claim **42**, wherein determining that said write operation is a commutable operation includes determining that said write operation includes inserting a record at a specified location.

45. The computing system of claim **39**, said processor further configured to, after suspending said spawner, set a deadline, thereby providing time for any spawn having said first task generation-indicator to execute to completion, and avoiding overhead associated with having to save states of said spawn having said first generation-indicator.

46. The computing system of claim **45**, said processor further configured to suspend said first spawn if said first spawn is still executing as of said deadline.

47. The computing system of claim **45**, said processor further configured to enable said first spawn to avoid suspension as a result of having failed to complete execution by said deadline.

48. The computing system of claim **47**, wherein enabling said first spawn to avoid suspension as a result of having failed to complete execution by said deadline includes changing said first task generation-indicator

to said second task generation-indicator in said first spawn if said first spawn is still executing as of said deadline.

49. The computing system of claim **39**, wherein said first node has a nodal-generation indicator, said processor further configured to cause a spawn to become a migrant that migrates to a second node, wherein said second node has a nodal-generation indicator.

50. The computing system of claim **49**, wherein said nodal-generation counter of said second node indicates that said second node is in a younger generation than said first node, said processor further configured to youthen said migrant to cause a generation indicator value of the migrant to be changed to indicate a younger generation value associated with the migrant.

51. The computing system of claim **50**, wherein youthening said migrant includes immigration-side youthening of said migrant.

52. The computing system of claim **50**, wherein youthening said migrant includes emigration-side youthening of said migrant.

53. The computing system of claim **39**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, wherein said multi-node system includes at least a second node, wherein, upon recovery following a failure of said second node, said first node rolls back to a state that corresponds to a nodal-generation count of said second node.

54. The computing system of claim **39**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, wherein said multi-node system includes at least a second node, wherein, upon recovery following a failure of said first node, said first node rolls forward to a state that corresponds to a nodal-generation count of said second node by restoring committed work from a checkpoint and restoring uncommitted work from a journal.

55. The computing system of claim **39**, wherein said first node is a node in a multi-node system in which each node has a nodal generation-count, said the processor further configured to, at said first node,

receive, from a master node, a message indicating that a checkpoint is to be carried out,

in response, youthen a nodal generation count of said first node to cause the nodal-generation count of said first node be changed to indicate a younger generation value associated with the first node,

suspend spawners from generating spawn,

save spawner recovery information for recovering spawner states,

resume said spawners,

determine that no further older-generation immigrants are expected at said first node, and

in response to said determination, commit, to said durable storage, said nodal recovery information.

56. The computing system of claim **55**, said processor further configured to set a deadline, and, upon lapse of said deadline, suspend all older-generation spawn that are still executing while younger-generation spawn continue to execute.

57. The computing system of claim **39**, wherein said first node is a node in a multi-node system, said processor further configured to save a replica copy of working memory of said first node at said second node, upon failure of said first node, temporarily using said replica copy for processing that would otherwise have been carried out by said first node, and, upon recovery of said first node, communicate, to said first node, information required to update memory in said first node so that subsequent computation can be carried out by said first node.

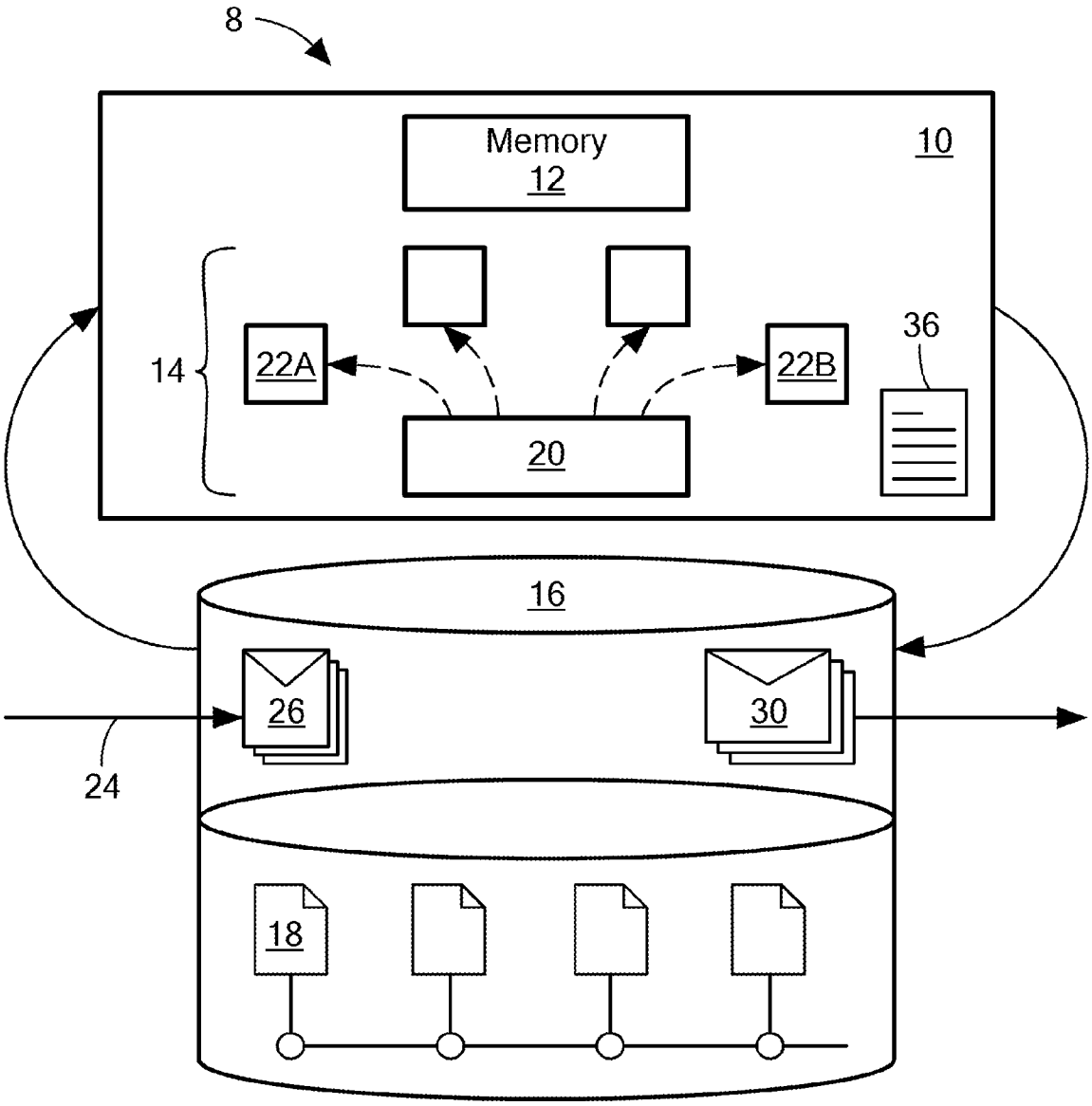


FIG. 1

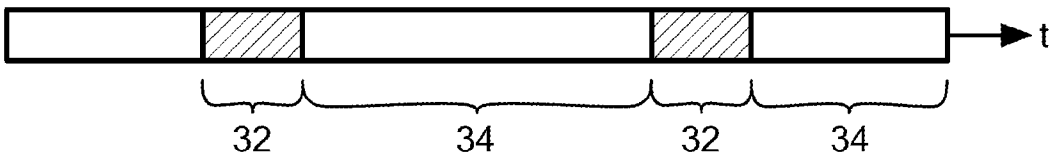


FIG. 2

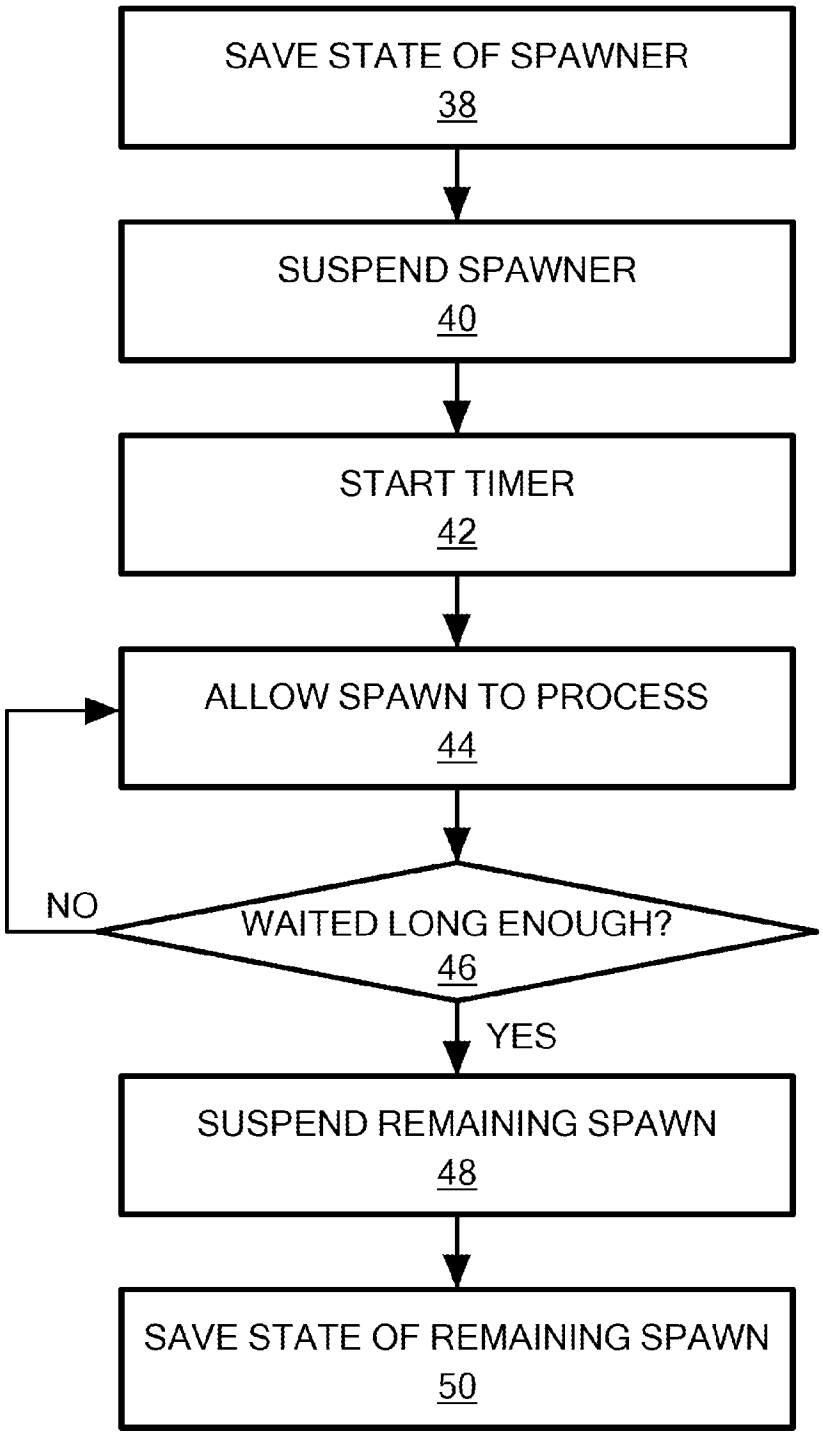

SAVE STATE OF SPAWNER
38
SUSPEND SPAWNER
40
START TIMER
42
ALLOW SPAWN TO PROCESS
44
NO
WAITED LONG ENOUGH?
46
YES
SUSPEND REMAINING SPAWN
48
SAVE STATE OF REMAINING SPAWN
50

FIG. 3

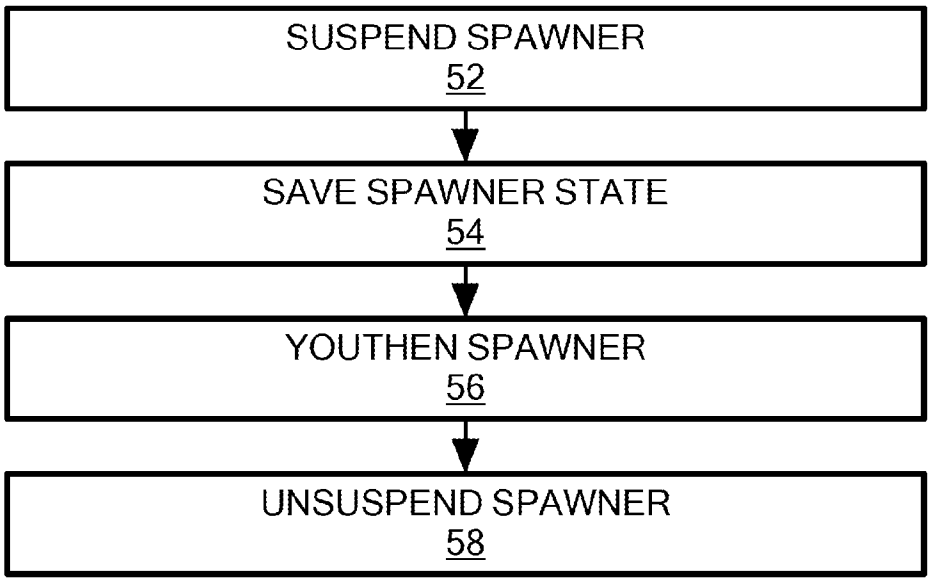

SUSPEND SPAWNER
52
SAVE SPAWNER STATE
54
YOUTHEN SPAWNER
56
UNSUSPEND SPAWNER
58

FIG. 4

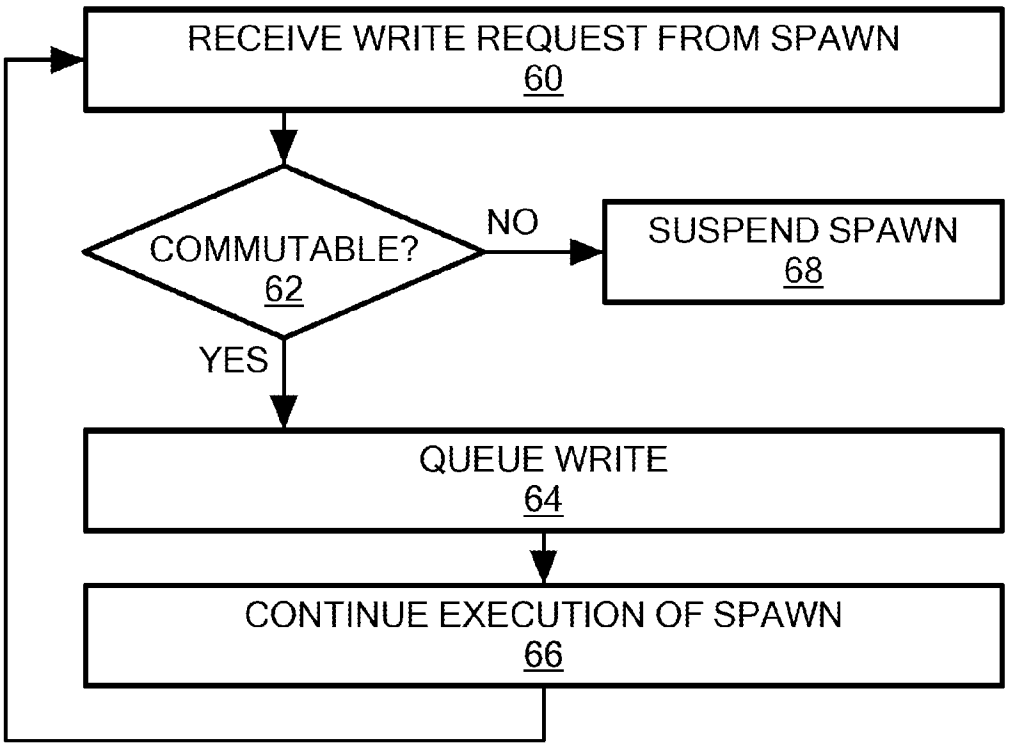

RECEIVE WRITE REQUEST FROM SPAWN
60
COMMUTABLE?
62
NO
SUSPEND SPAWN
68
YES
QUEUE WRITE
64
CONTINUE EXECUTION OF SPAWN
66

FIG. 5

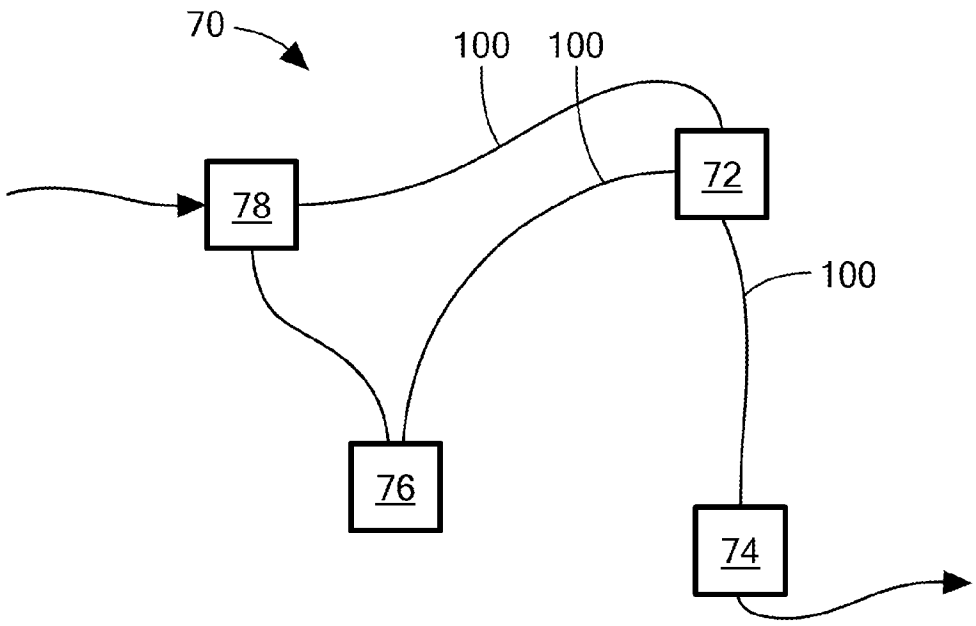


FIG. 6

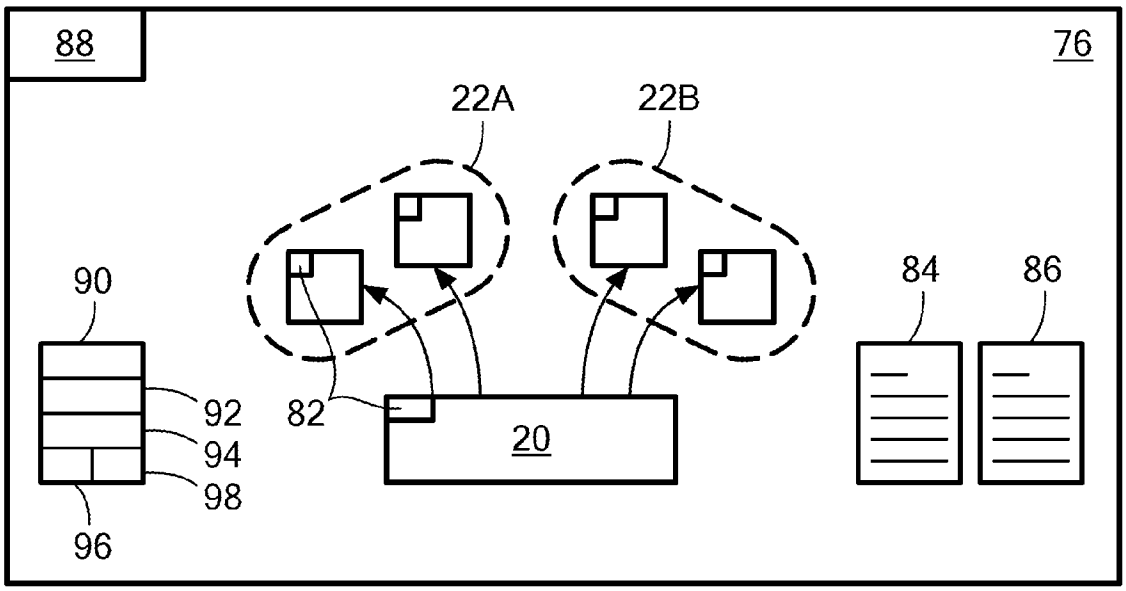


FIG. 7

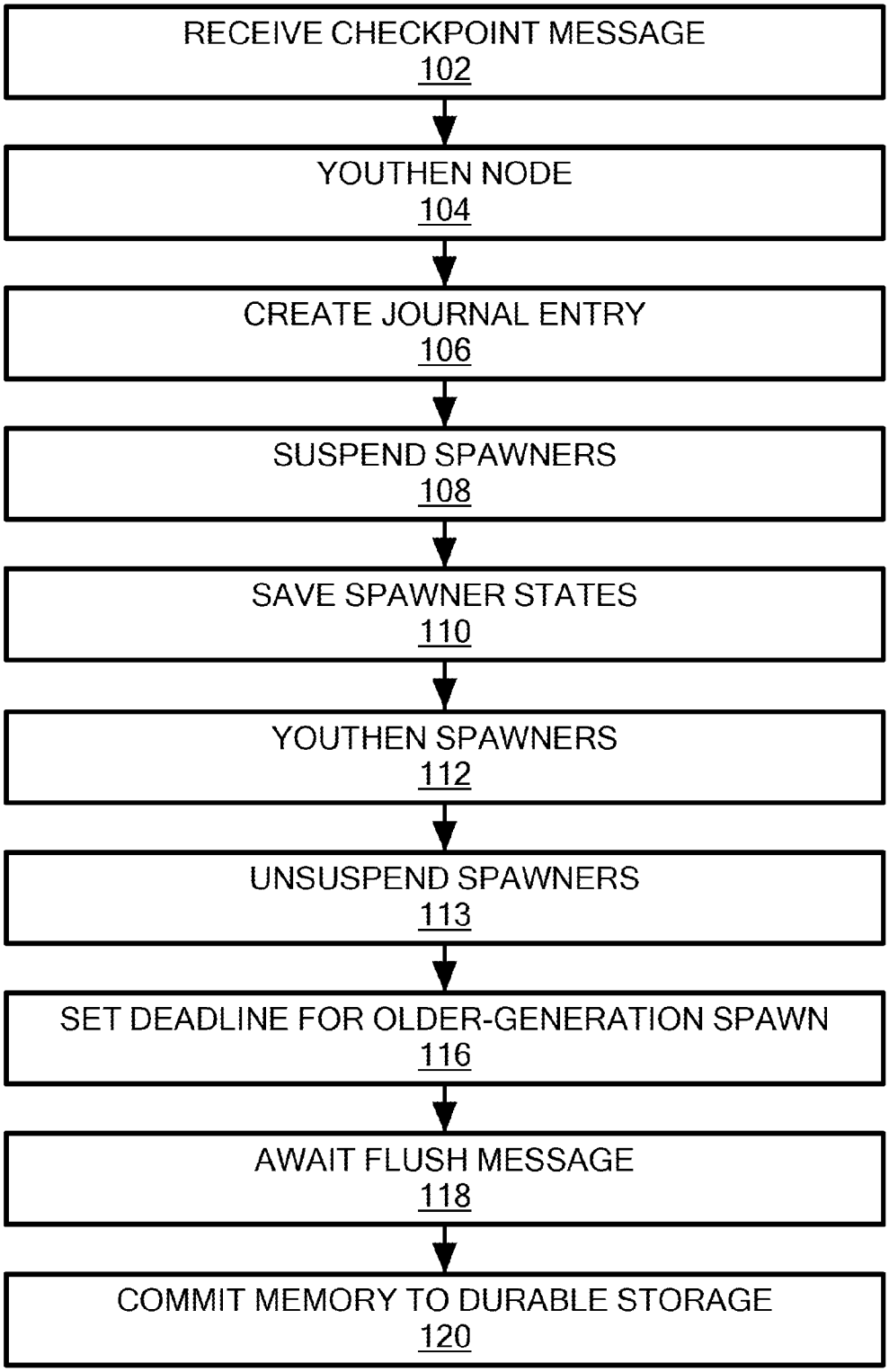

RECEIVE CHECKPOINT MESSAGE
102
YOUTHEN NODE
104
CREATE JOURNAL ENTRY
106
SUSPEND SPAWNERS
108
SAVE SPAWNER STATES
110
YOUTHEN SPAWNERS
112
UNSUSPEND SPAWNERS
113
SET DEADLINE FOR OLDER-GENERATION SPAWN
116
AWAIT FLUSH MESSAGE
118
COMMIT MEMORY TO DURABLE STORAGE
120

FIG. 8

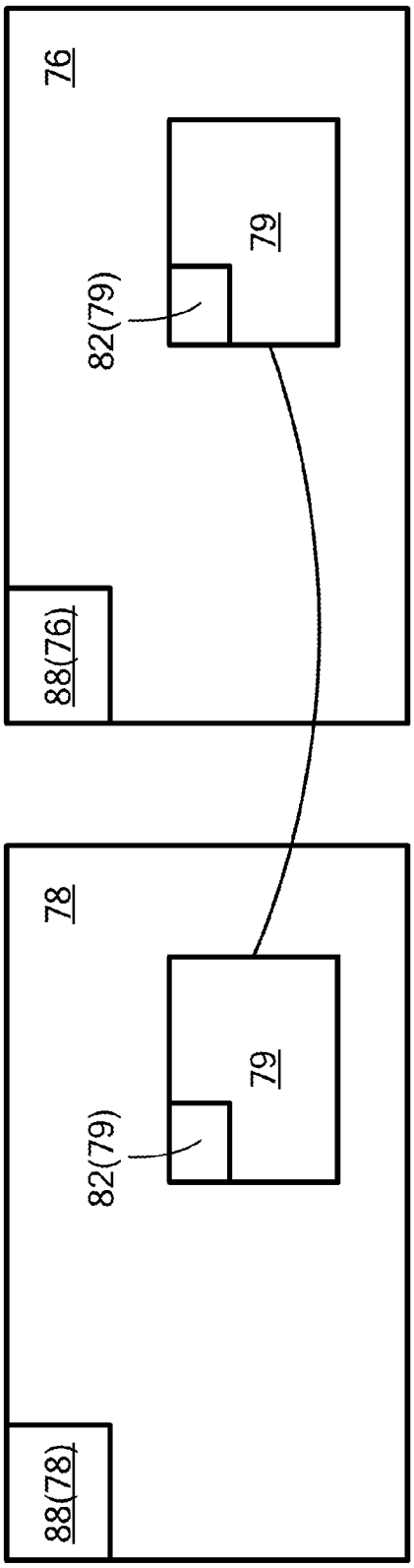

76
79
82(79)
88(76)
78
79
82(79)
88(78)
IF 82(79)<88(76)
{82(79)++;
JOURNALIZE(79)}
END IF
IF 82(79)<88(79)
{82(79)++;
JOURNALIZE(79)}
END IF

FIG. 9

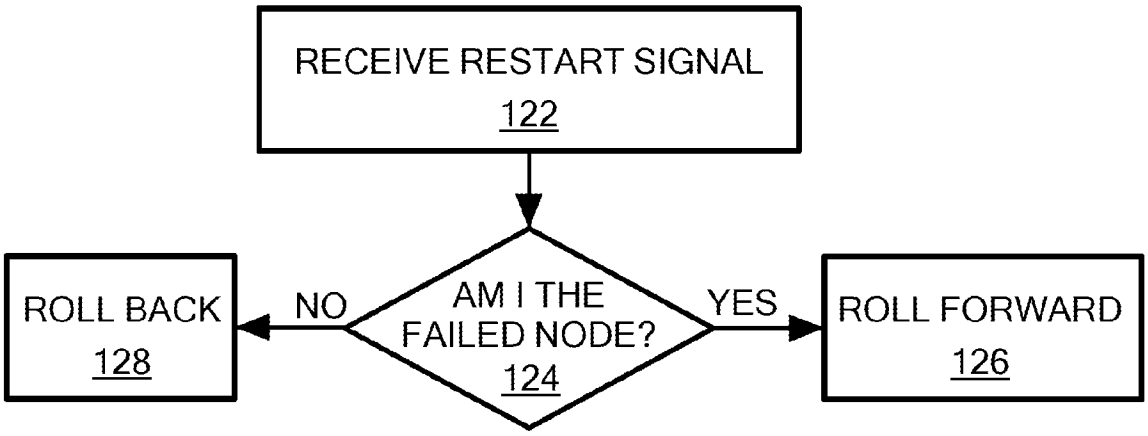

RECEIVE RESTART SIGNAL
122
AM I THE FAILED NODE?
124
NO
YES
ROLL BACK
128
ROLL FORWARD
126

FIG. 10

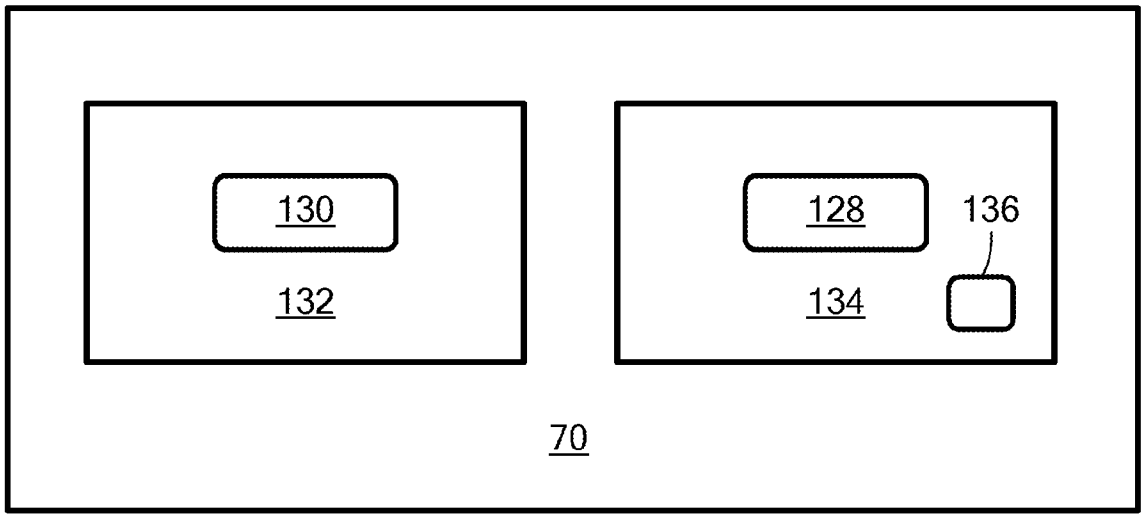

130
132
128
134
136
70

FIG. 11

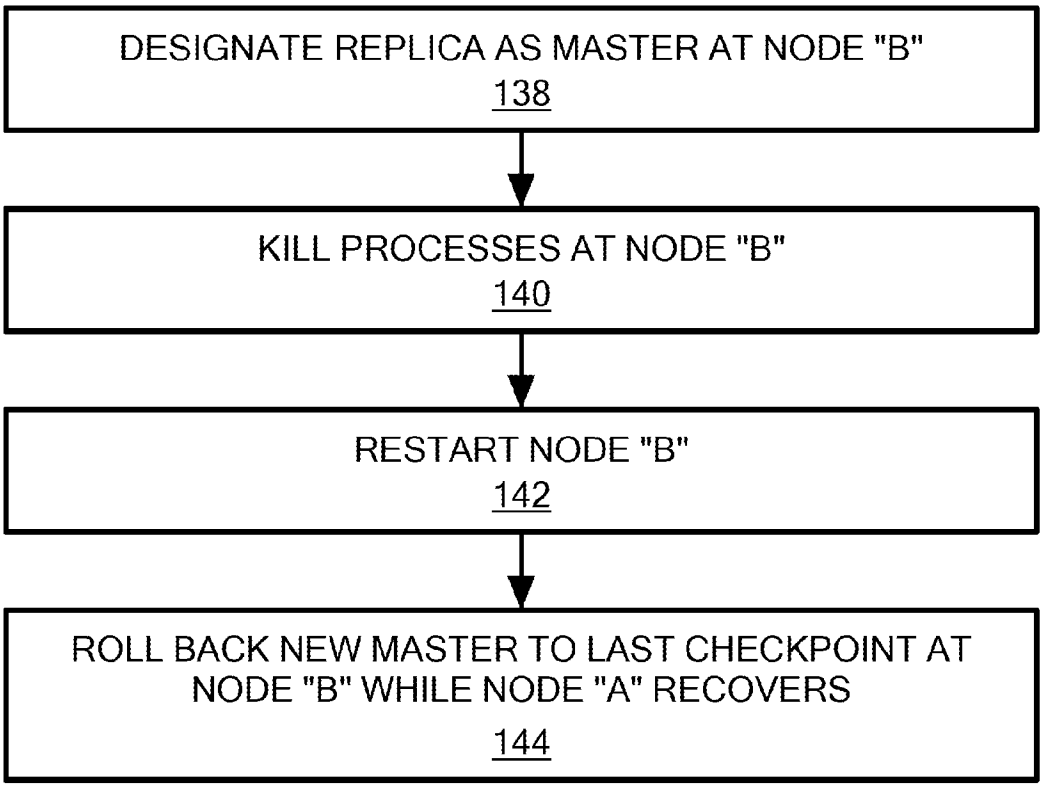

DESIGNATE REPLICA AS MASTER AT NODE "B"
138
KILL PROCESSES AT NODE "B"
140
RESTART NODE "B"
142
ROLL BACK NEW MASTER TO LAST CHECKPOINT AT NODE "B" WHILE NODE "A" RECOVERS
144

FIG. 12

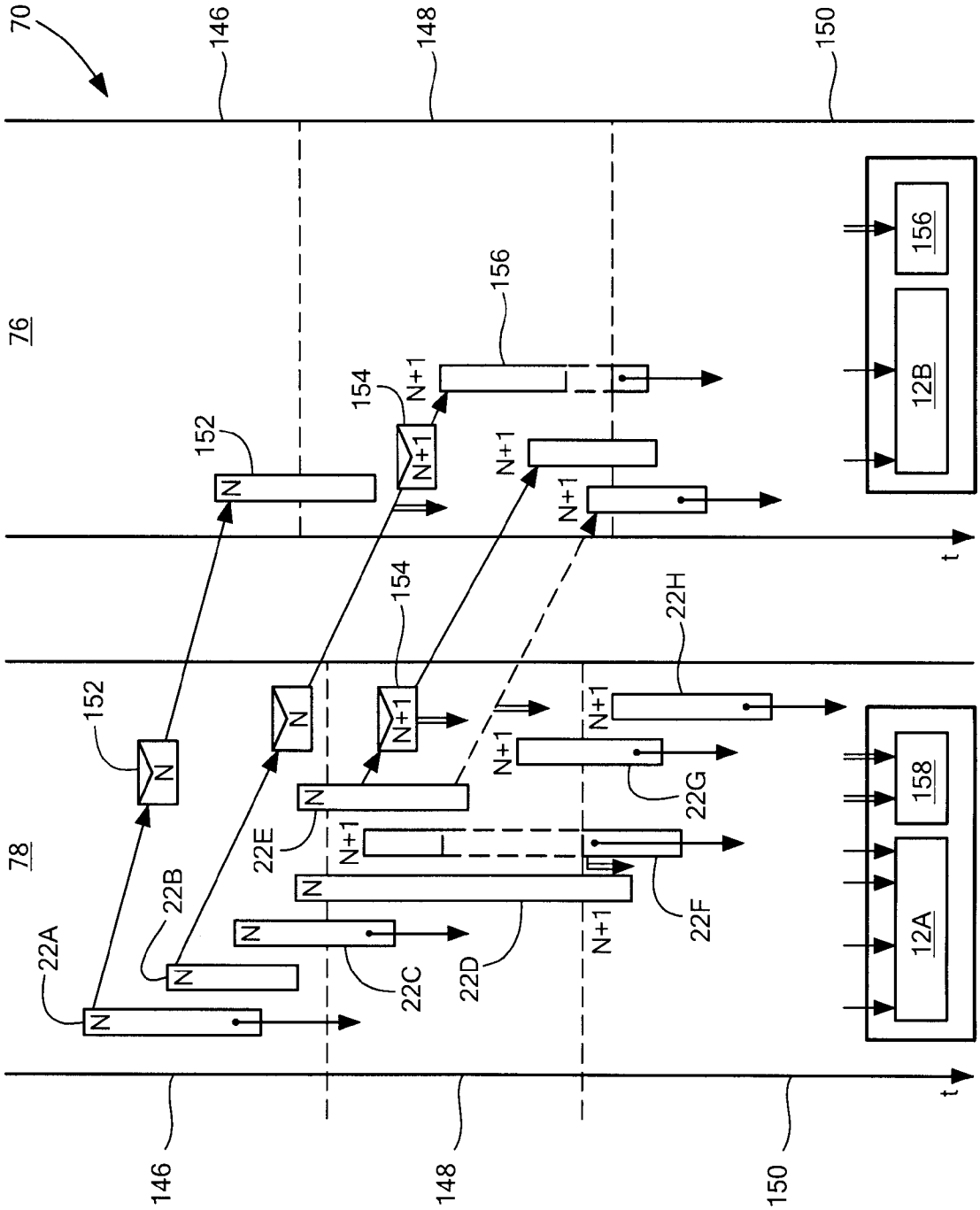
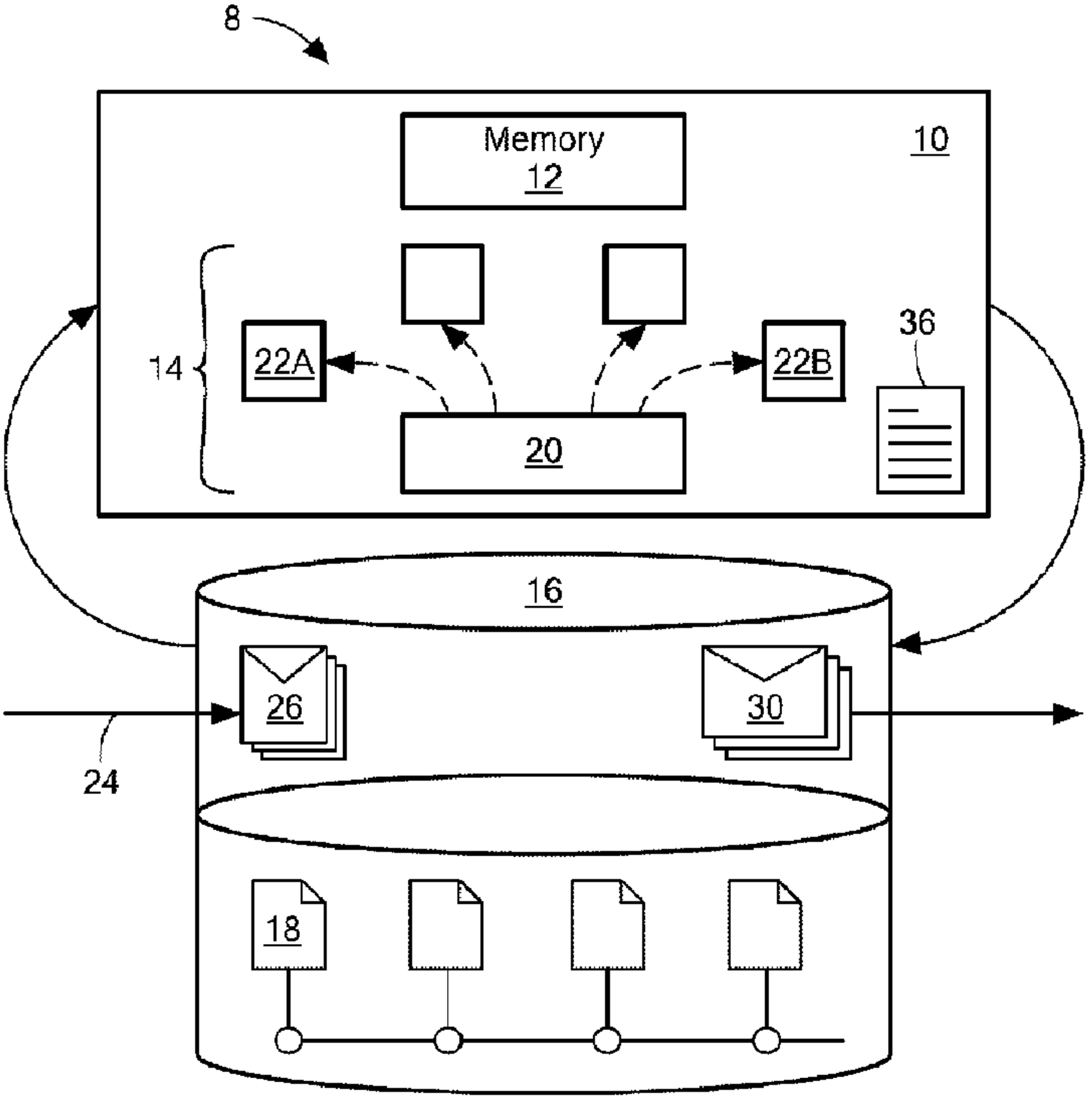

70
146
148
150
76
78
152
154
156
N
N+1
22A
22B
22C
22D
22E
22F
22G
22H
12A
12B
158
t

FIG. 13


8
Memory
12
10
14
22A
22B
36
20
16
26
30
24
18