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(54) **DETERMINING A JOB GROUP STATUS BASED ON A RELATIONSHIP BETWEEN A GENERATION COUNTER VALUE AND A TICKET VALUE FOR SCHEDULING THE JOB GROUP FOR EXECUTION**

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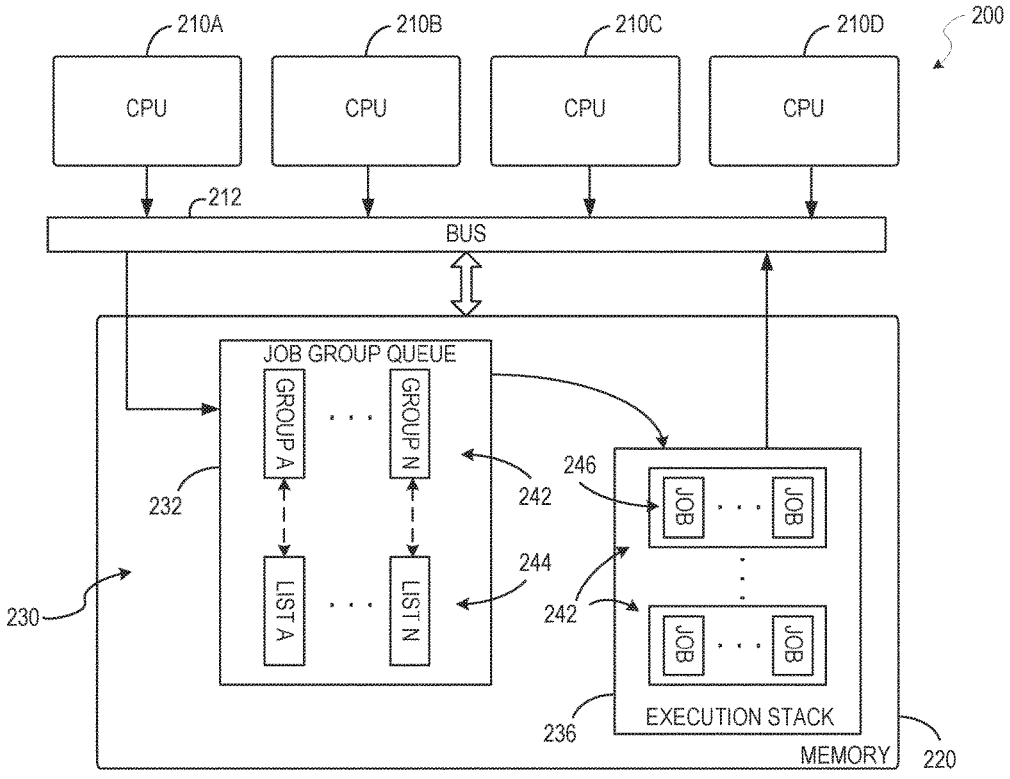
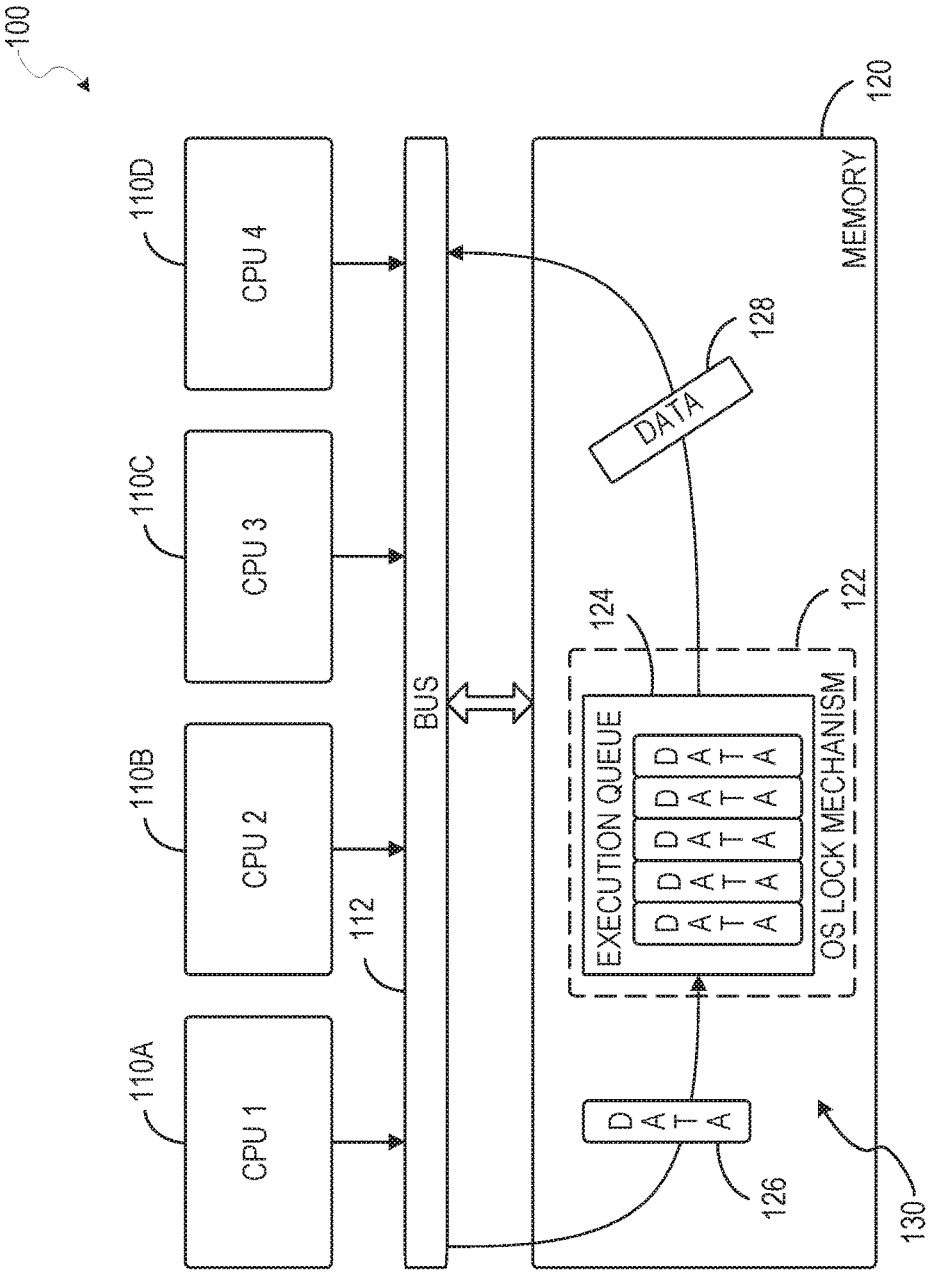
(57) **ABSTRACT**

A job scheduler system includes one or more hardware processors, a memory including a job group queue stored in the memory, and a job scheduler engine configured to create a first job group in the job group queue, the first job group includes a generation counter having an initial value, receive a first request to steal the first job group, determine a state of the first job group based at least in part on the generation counter, the state indicating that the first job group is available to steal, based on the determining the state of the first job group, atomically increment the generation counter, thereby making the first job group unavailable for stealing, and alter an execution order of the first job group ahead of at least one other job group in the job group queue.





PRIOR ART

Figure 1

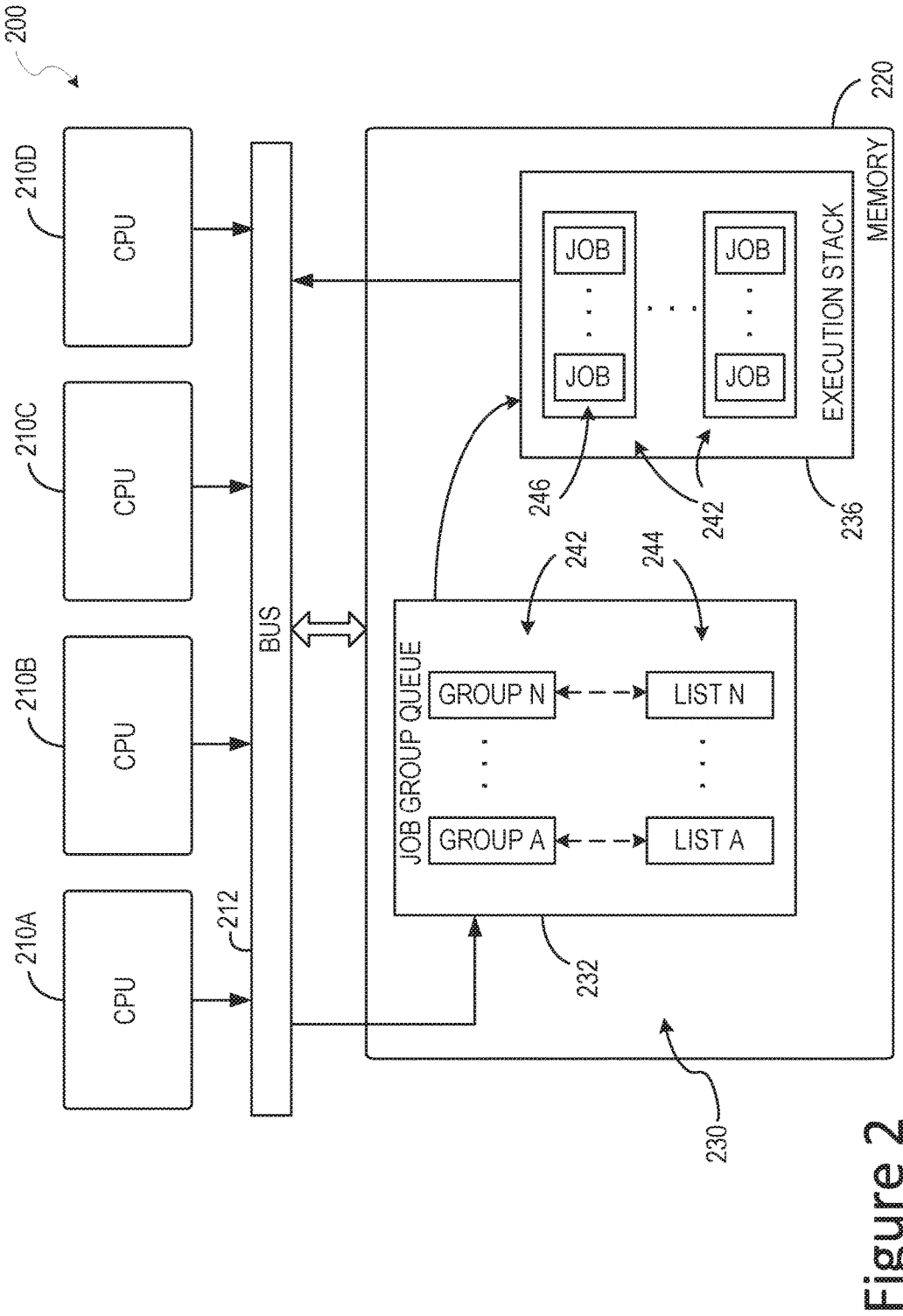

200
210D
CPU
210C
CPU
210B
CPU
210A
CPU
212
BUS
220
MEMORY
EXECUTION STACK
JOB
JOB
JOB
JOB
246
242
236
242
244
JOB GROUP QUEUE
GROUP N
LIST N
GROUP A
LIST A
232
230

Figure 2

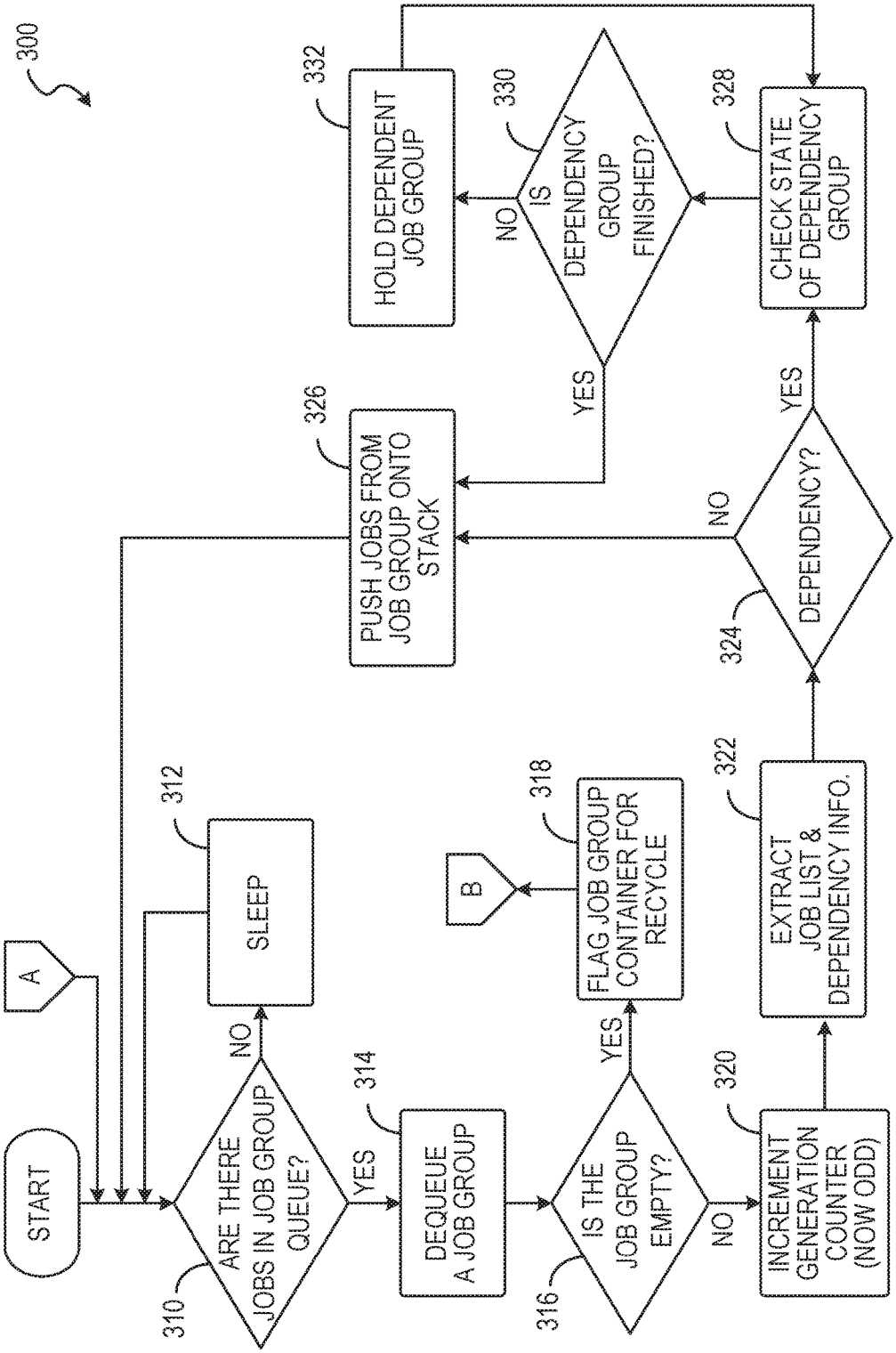

300
START
A
ARE THERE JOBS IN JOB GROUP QUEUE?
310
NO
SLEEP
312
YES
DEQUEUE A JOB GROUP
314
IS THE JOB GROUP EMPTY?
316
YES
B
FLAG JOB GROUP CONTAINER FOR RECYCLE
318
NO
INCREMENT GENERATION COUNTER (NOW ODD)
320
EXTRACT JOB LIST & DEPENDENCY INFO.
322
DEPENDENCY?
324
NO
PUSH JOBS FROM JOB GROUP ONTO STACK
326
YES
IS DEPENDENCY GROUP FINISHED?
330
NO
HOLD DEPENDENT JOB GROUP
332
YES
CHECK STATE OF DEPENDENCY GROUP
328

Figure 3A

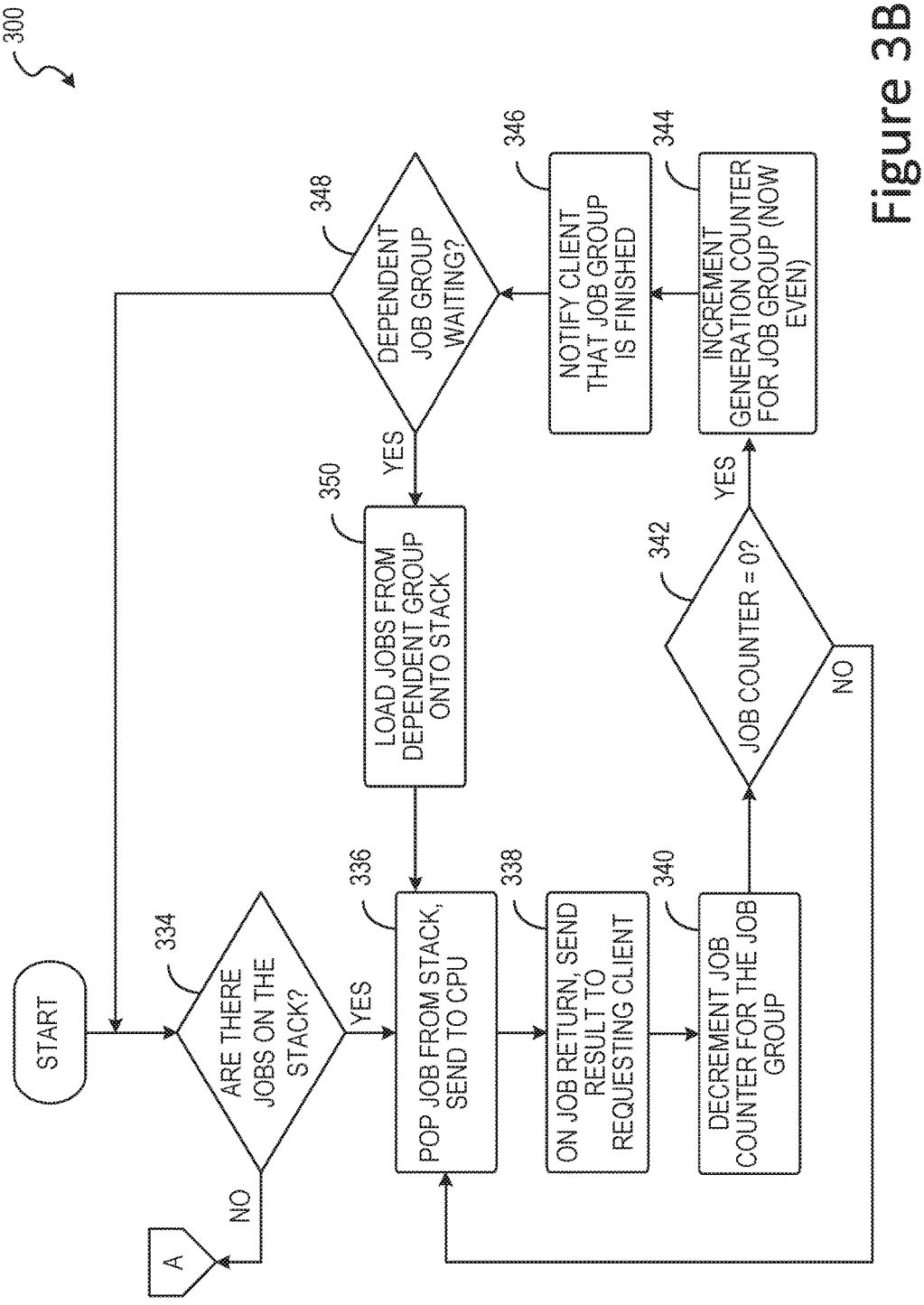

300
START
334
ARE THERE JOBS ON THE STACK?
YES
NO
A
336
POP JOB FROM STACK, SEND TO CPU
338
ON JOB RETURN, SEND RESULT TO REQUESTING CLIENT
340
DECREMENT JOB COUNTER FOR THE JOB GROUP
342
JOB COUNTER = 0?
YES
NO
344
INCREMENT GENERATION COUNTER FOR JOB GROUP (NOW EVEN)
346
NOTIFY CLIENT THAT JOB GROUP IS FINISHED
348
DEPENDENT JOB GROUP WAITING?
YES
350
LOAD JOBS FROM DEPENDENT GROUP ONTO STACK

Figure 3B

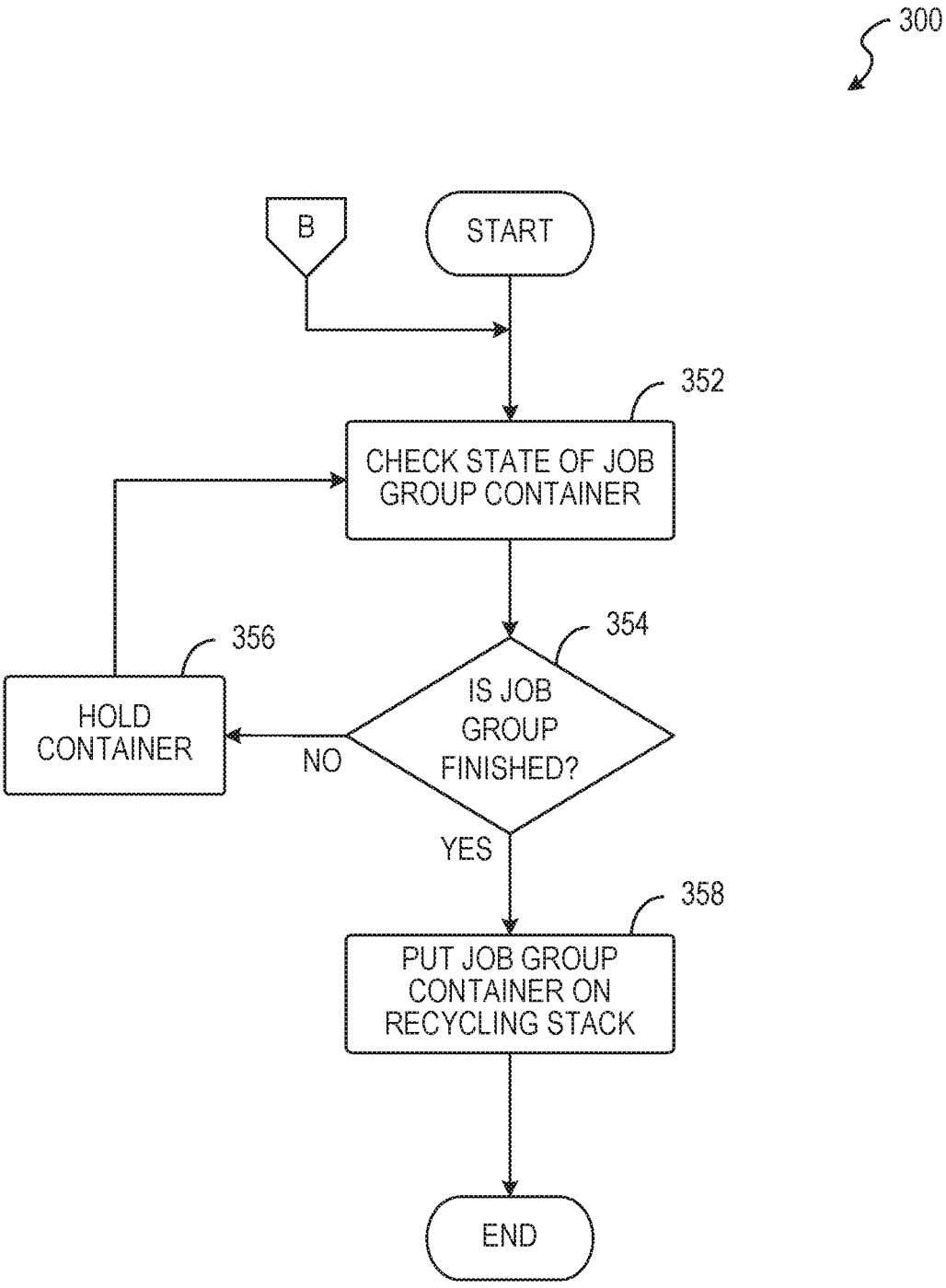

300
B
START
352
CHECK STATE OF JOB GROUP CONTAINER
354
IS JOB GROUP FINISHED?
NO
356
HOLD CONTAINER
YES
358
PUT JOB GROUP CONTAINER ON RECYCLING STACK
END

Figure 3C

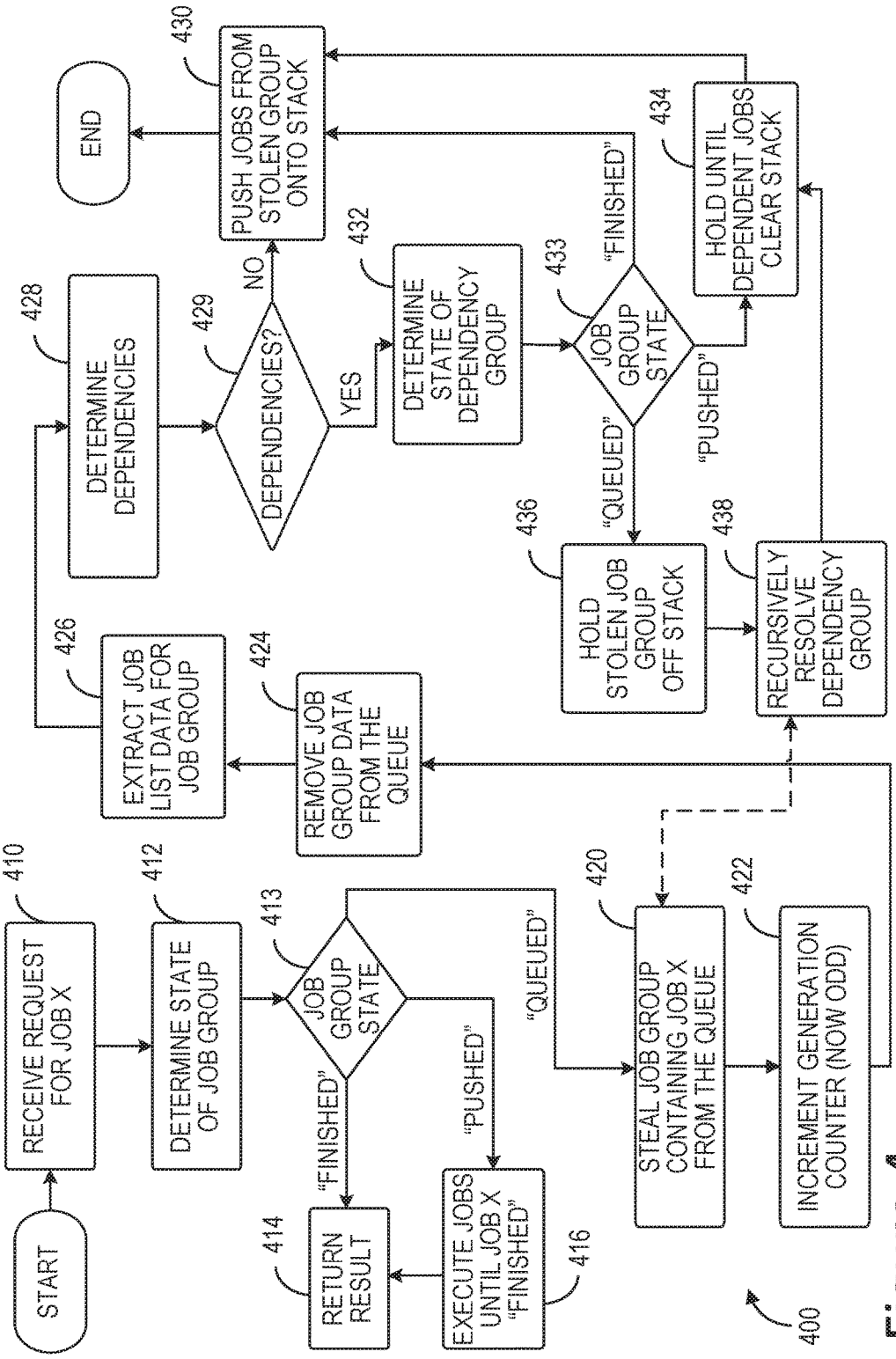

START
RECEIVE REQUEST FOR JOB X
410
DETERMINE STATE OF JOB GROUP
412
JOB GROUP STATE
413
"FINISHED"
"PUSHED"
"QUEUED"
RETURN RESULT
414
EXECUTE JOBS UNTIL JOB X "FINISHED"
416
STEAL JOB GROUP CONTAINING JOB X FROM THE QUEUE
420
INCREMENT GENERATION COUNTER (NOW ODD)
422
400
REMOVE JOB GROUP DATA FROM THE QUEUE
424
EXTRACT JOB LIST DATA FOR JOB GROUP
426
DETERMINE DEPENDENCIES
428
DEPENDENCIES?
429
NO
YES
PUSH JOBS FROM STOLEN GROUP ONTO STACK
430
END
DETERMINE STATE OF DEPENDENCY GROUP
432
JOB GROUP STATE
433
"FINISHED"
"PUSHED"
"QUEUED"
HOLD UNTIL DEPENDENT JOBS CLEAR STACK
434
HOLD STOLEN JOB GROUP OFF STACK
436
RECURSIVELY RESOLVE DEPENDENCY GROUP
438

Figure 4

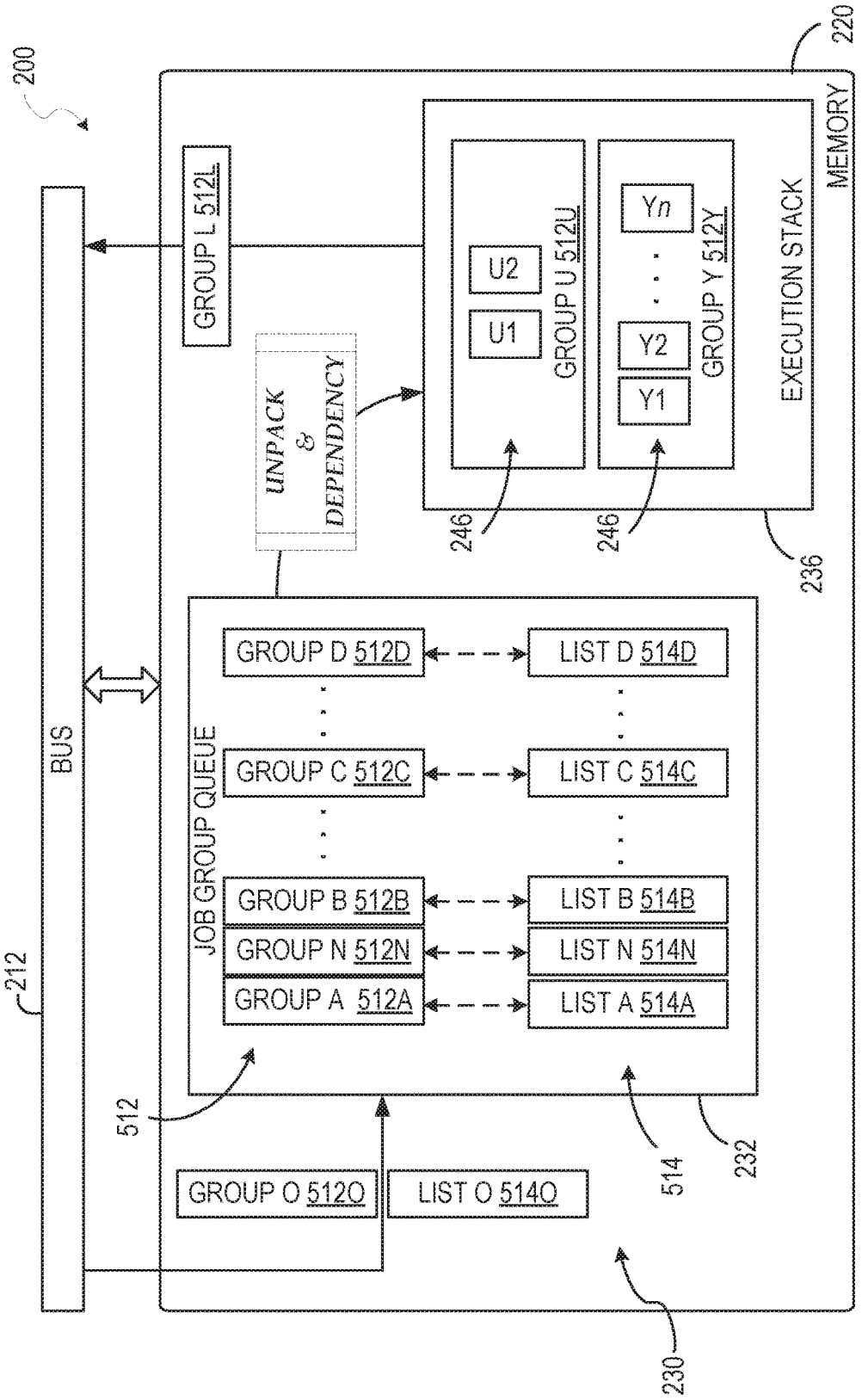

200
220
MEMORY
EXECUTION STACK
GROUP L 512L
GROUP U 512U
U2
U1
GROUP Y 512Y
Yn
Y2
Y1
UNPACK & DEPENDENCY
246
246
236
BUS
212
JOB GROUP QUEUE
GROUP D 512D
LIST D 514D
GROUP C 512C
LIST C 514C
GROUP B 512B
LIST B 514B
GROUP N 512N
LIST N 514N
GROUP A 512A
LIST A 514A
512
514
232
GROUP O 512O
LIST O 514O
230

Figure 5

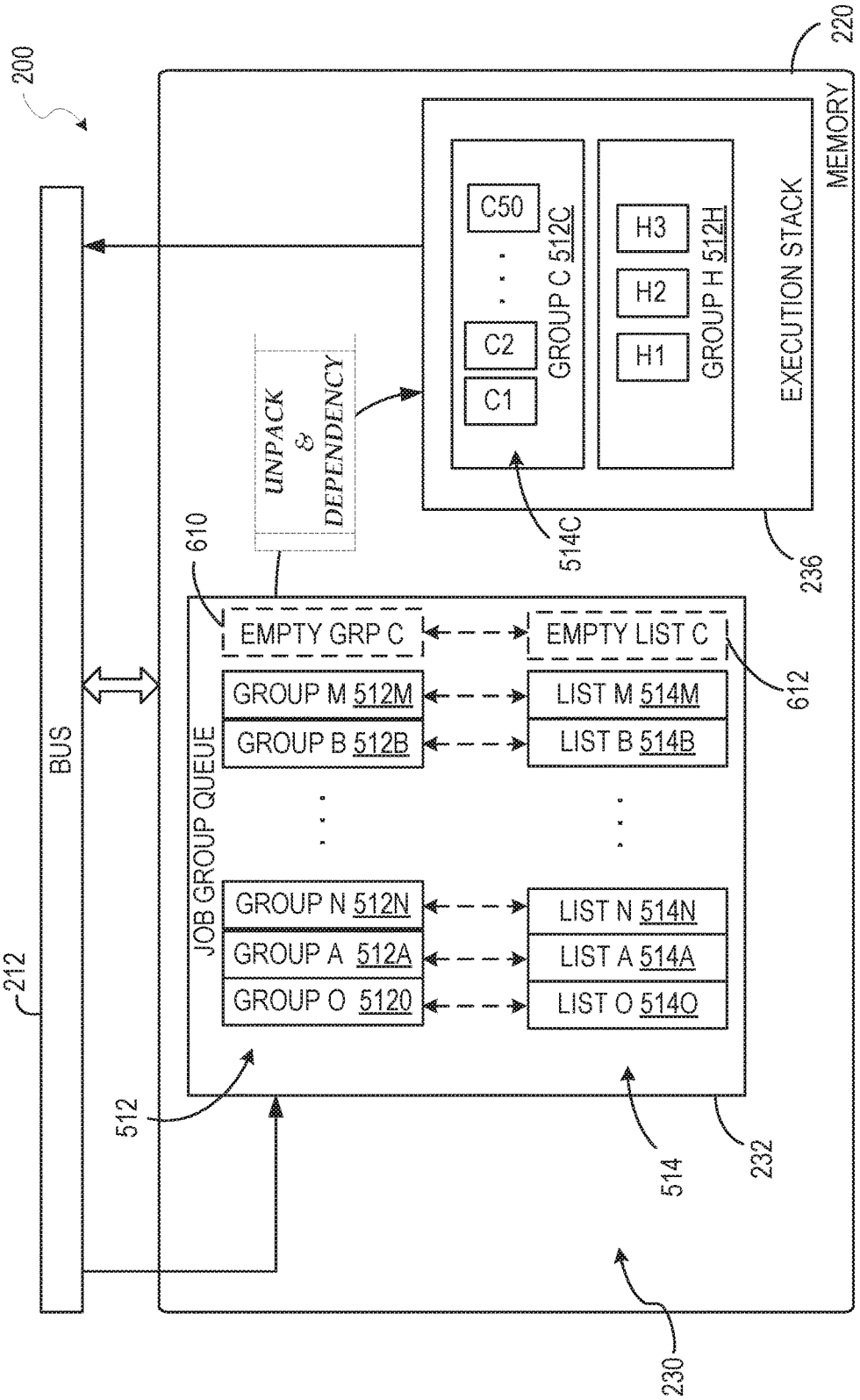

200
220
MEMORY
EXECUTION STACK
C50
C2
C1
GROUP C 512C
H3
H2
H1
GROUP H 512H
UNPACK & DEPENDENCY
514C
236
610
EMPTY GRP C
EMPTY LIST C
612
GROUP M 512M
LIST M 514M
GROUP B 512B
LIST B 514B
JOB GROUP QUEUE
GROUP N 512N
LIST N 514N
GROUP A 512A
LIST A 514A
GROUP O 5120
LIST O 514O
BUS
212
512
514
232
230

Figure 6

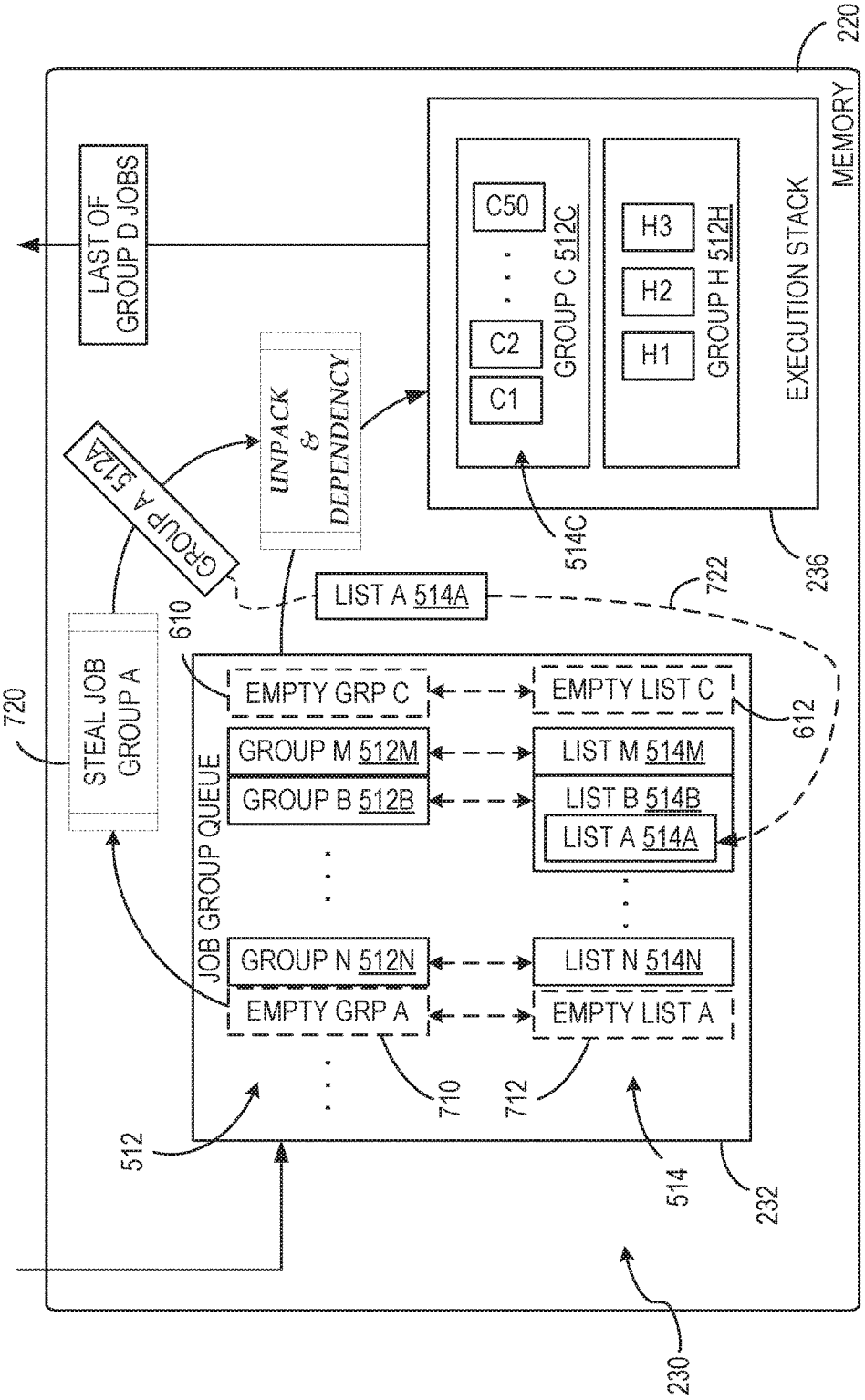

220
MEMORY
EXECUTION STACK
GROUP H 512H
H3
H2
H1
GROUP C 512C
C50
C2
C1
514C
236
LAST OF GROUP D JOBS
UNPACK & DEPENDENCY
GROUP A 512A
LIST A 514A
722
610
720
STEAL JOB GROUP A
JOB GROUP QUEUE
EMPTY GRP C
EMPTY LIST C
612
GROUP M 512M
LIST M 514M
GROUP B 512B
LIST B 514B
LIST A 514A
GROUP N 512N
LIST N 514N
EMPTY GRP A
EMPTY LIST A
710
712
512
514
232
230

Figure 7

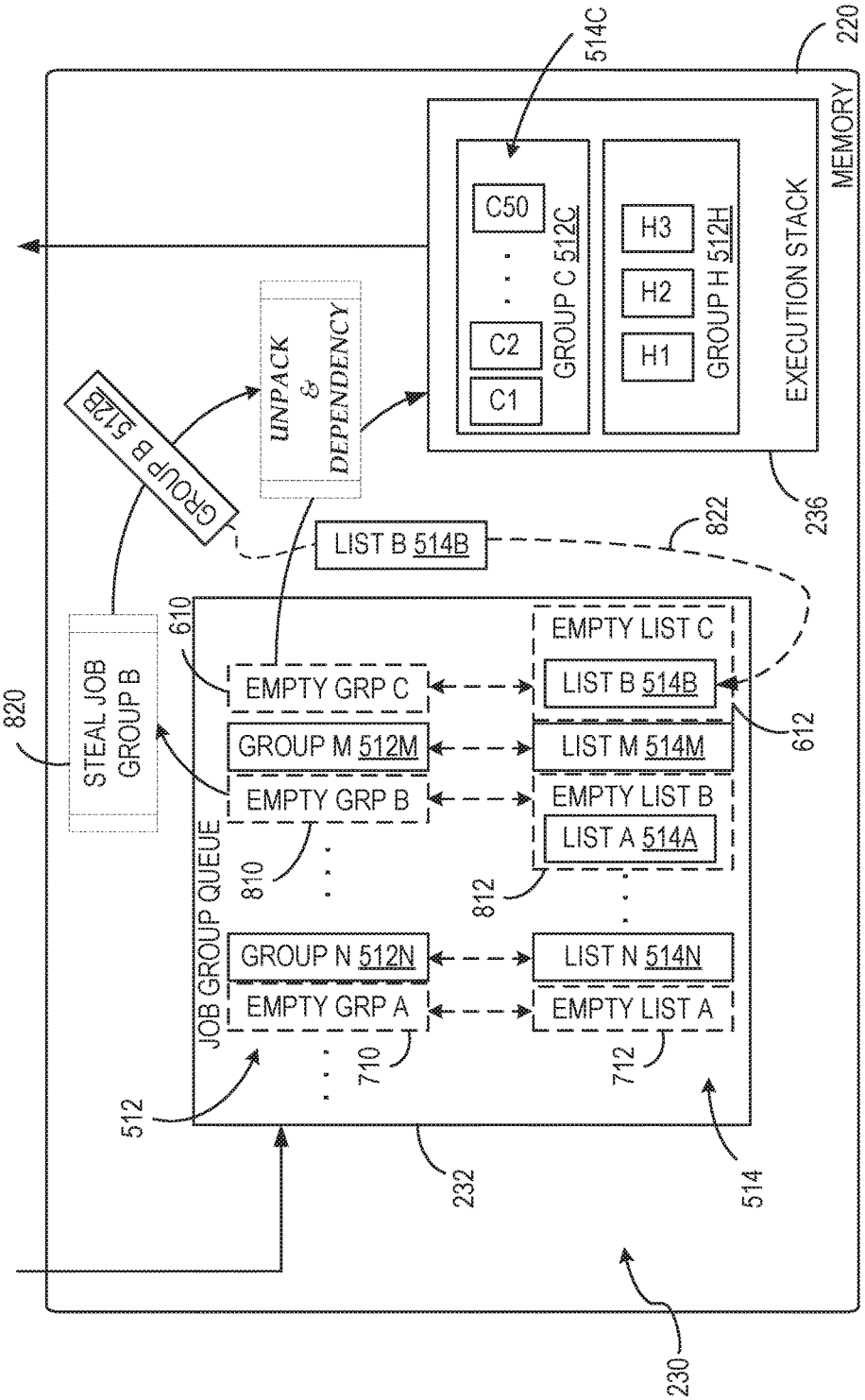

514C
220
MEMORY
C50
C2
C1
GROUP C 512C
H3
H2
H1
GROUP H 512H
EXECUTION STACK
236
UNPACK & DEPENDENCY
GROUP B 512B
LIST B 514B
822
610
EMPTY LIST C
EMPTY GRP C
LIST B 514B
612
GROUP M 512M
LIST M 514M
EMPTY GRP B
EMPTY LIST B
LIST A 514A
820
STEAL JOB GROUP B
JOB GROUP QUEUE
810
812
GROUP N 512N
LIST N 514N
EMPTY GRP A
EMPTY LIST A
710
712
512
232
514
230

Figure 8

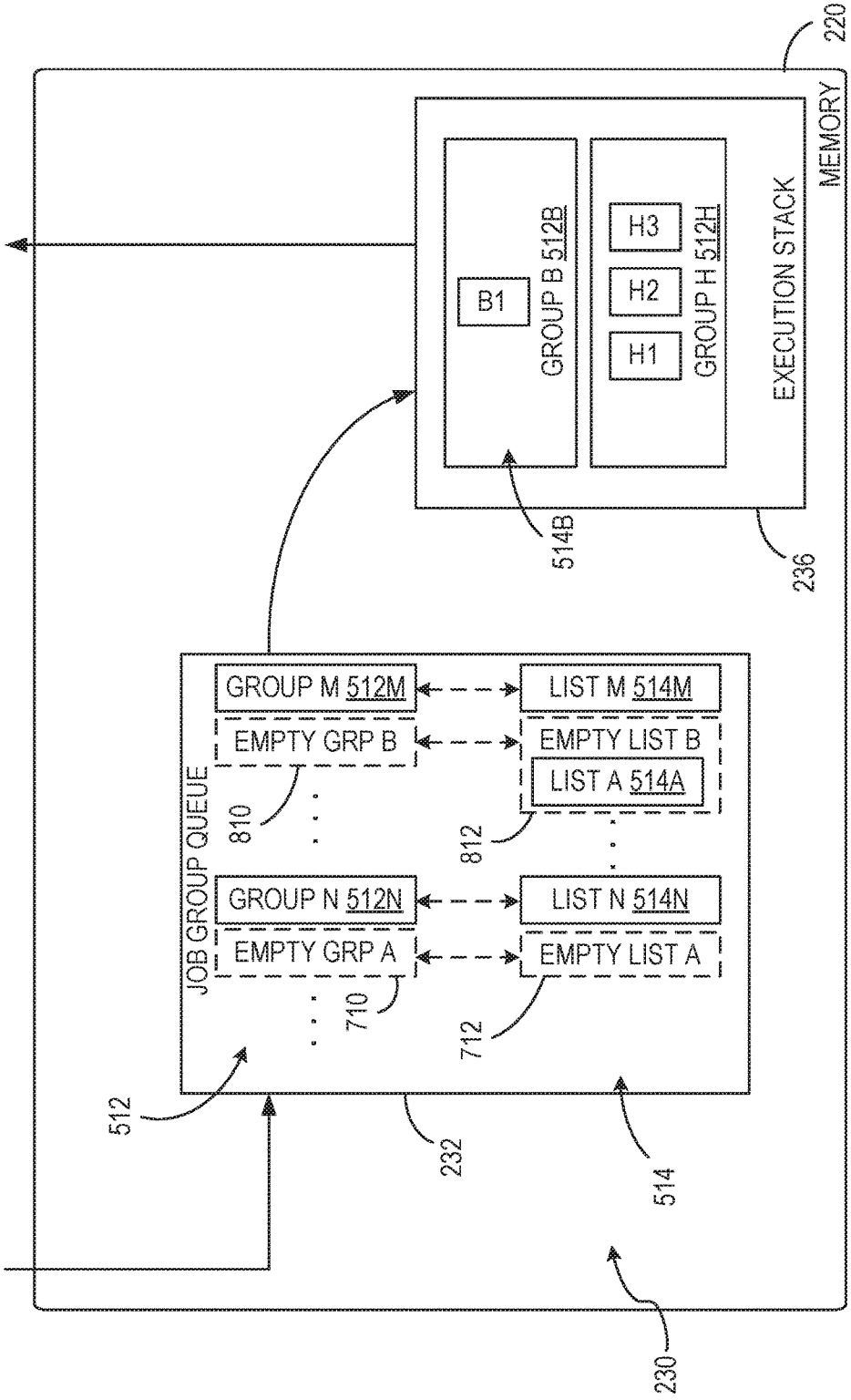

220
MEMORY
EXECUTION STACK
GROUP B 512B
B1
GROUP H 512H
H3
H2
H1
514B
236
JOB GROUP QUEUE
GROUP M 512M
LIST M 514M
EMPTY GRP B
EMPTY LIST B
LIST A 514A
810
812
GROUP N 512N
LIST N 514N
EMPTY GRP A
EMPTY LIST A
710
712
512
232
514
230

Figure 9

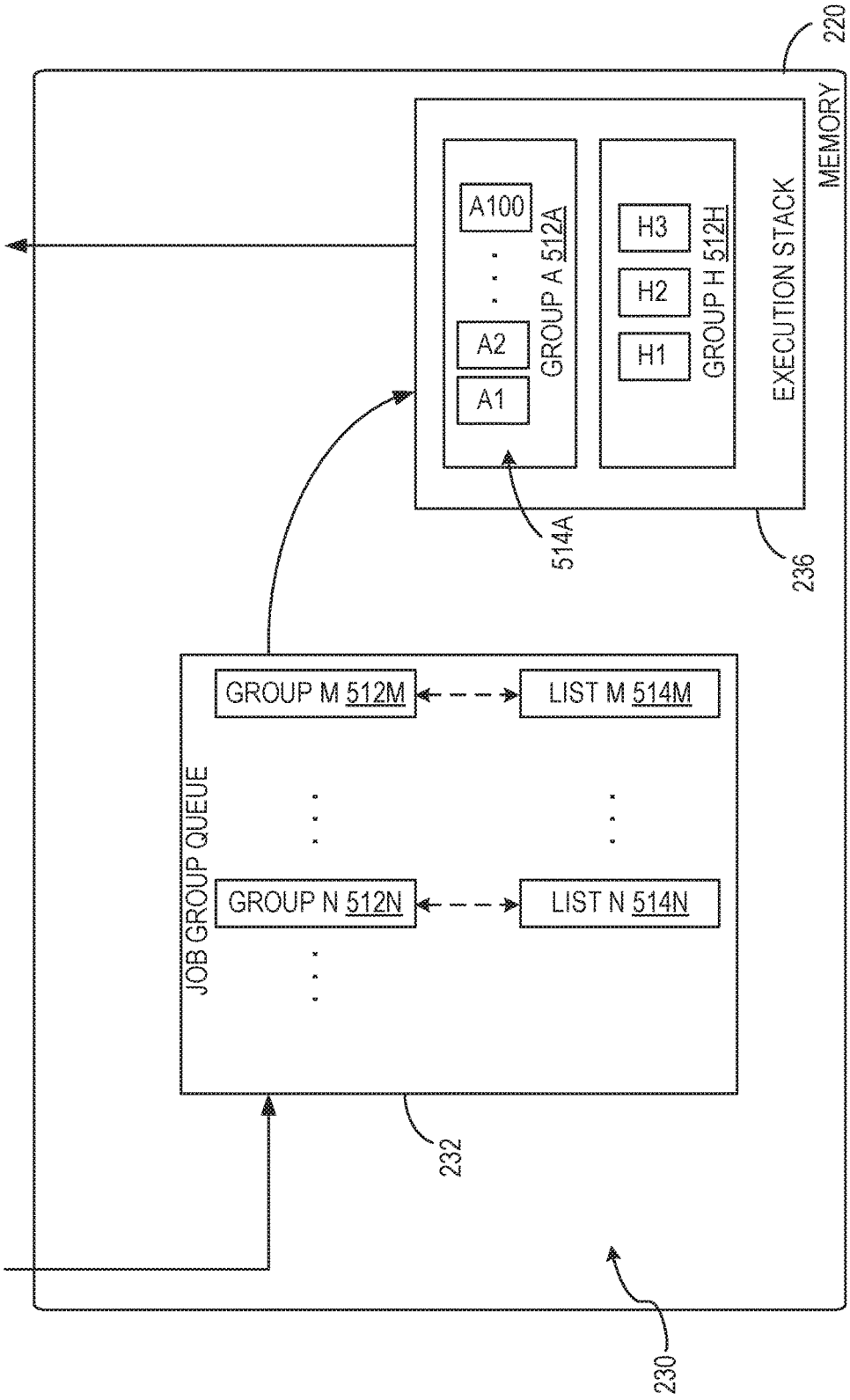

220
MEMORY
EXECUTION STACK
A100
A2
A1
GROUP A 512A
H3
H2
H1
GROUP H 512H
514A
236
JOB GROUP QUEUE
GROUP M 512M
LIST M 514M
GROUP N 512N
LIST N 514N
232
230

Figure 10

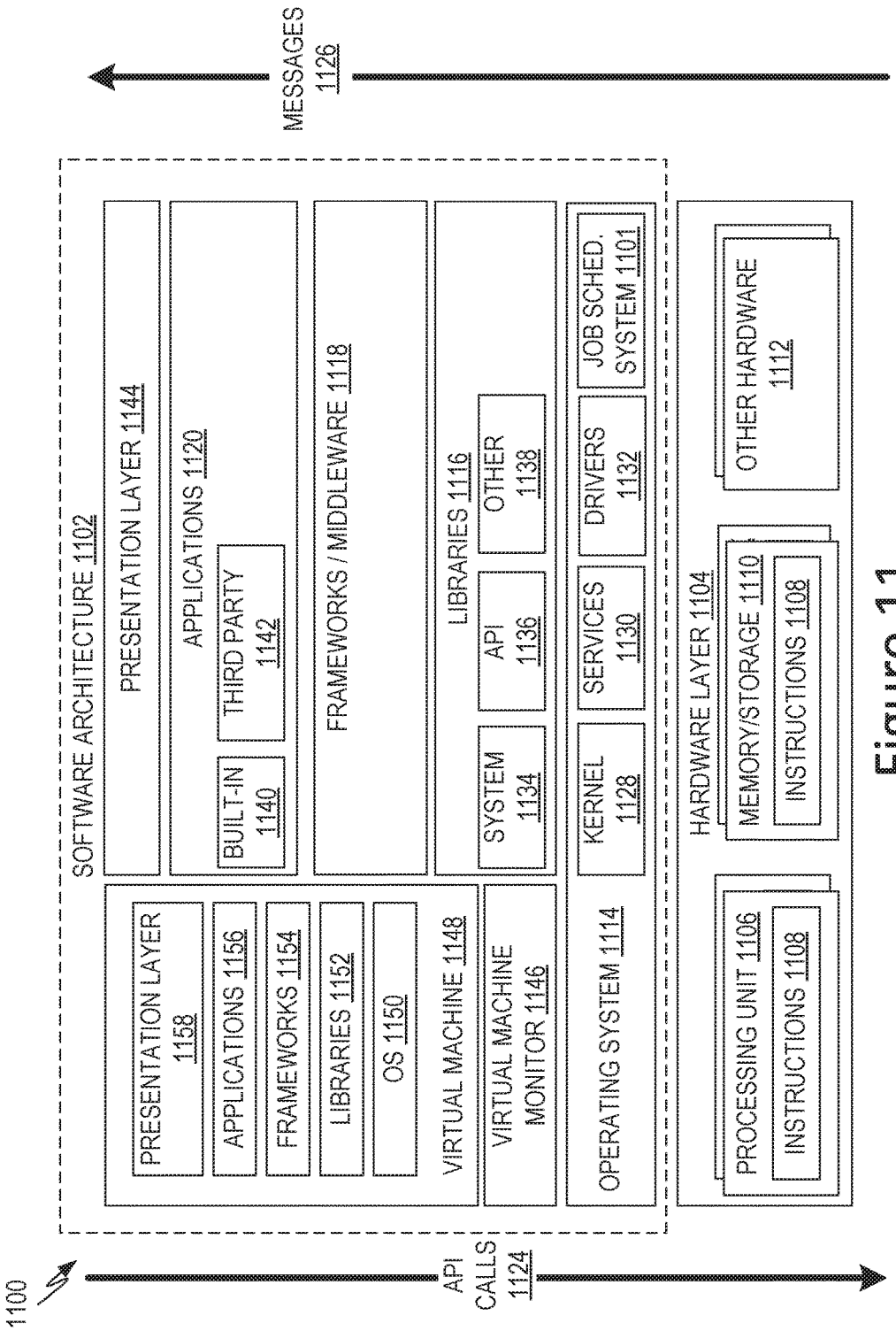

1100
API CALLS 1124
MESSAGES 1126
SOFTWARE ARCHITECTURE 1102
PRESENTATION LAYER 1144
APPLICATIONS 1120
BUILT-IN 1140
THIRD PARTY 1142
FRAMEWORKS / MIDDLEWARE 1118
LIBRARIES 1116
SYSTEM 1134
API 1136
OTHER 1138
VIRTUAL MACHINE 1148
PRESENTATION LAYER 1158
APPLICATIONS 1156
FRAMEWORKS 1154
LIBRARIES 1152
OS 1150
VIRTUAL MACHINE MONITOR 1146
OPERATING SYSTEM 1114
KERNEL 1128
SERVICES 1130
DRIVERS 1132
JOB SCHED. SYSTEM 1101
HARDWARE LAYER 1104
PROCESSING UNIT 1106
INSTRUCTIONS 1108
MEMORY/STORAGE 1110
INSTRUCTIONS 1108
OTHER HARDWARE 1112

Figure 11

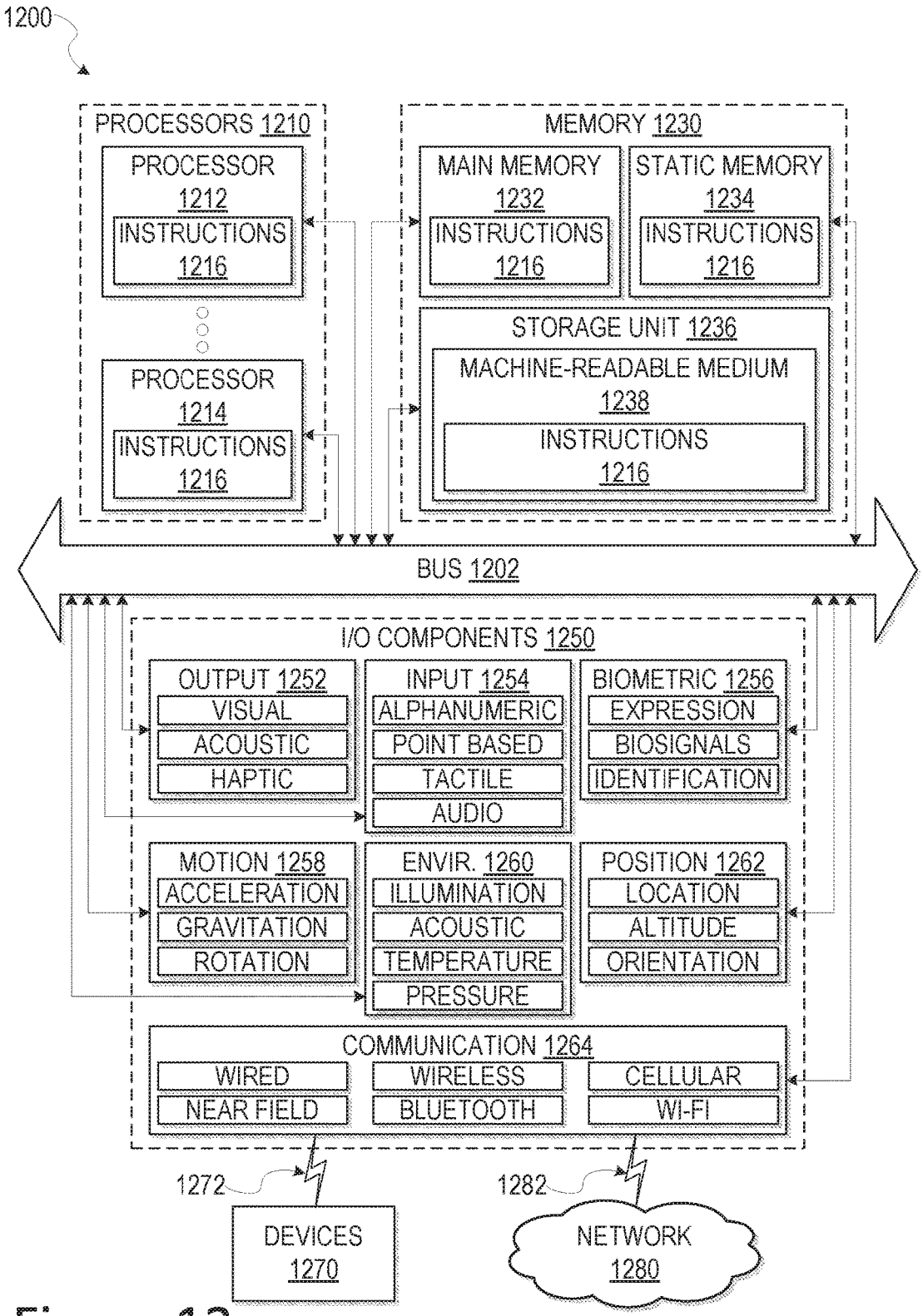

1200
PROCESSORS 1210
PROCESSOR 1212
INSTRUCTIONS 1216
PROCESSOR 1214
INSTRUCTIONS 1216
MEMORY 1230
MAIN MEMORY 1232
INSTRUCTIONS 1216
STATIC MEMORY 1234
INSTRUCTIONS 1216
STORAGE UNIT 1236
MACHINE-READABLE MEDIUM 1238
INSTRUCTIONS 1216
BUS 1202
I/O COMPONENTS 1250
OUTPUT 1252
VISUAL
ACOUSTIC
HAPTIC
INPUT 1254
ALPHANUMERIC
POINT BASED
TACTILE
AUDIO
BIOMETRIC 1256
EXPRESSION
BIOSIGNALS
IDENTIFICATION
MOTION 1258
ACCELERATION
GRAVITATION
ROTATION
ENVIR. 1260
ILLUMINATION
ACOUSTIC
TEMPERATURE
PRESSURE
POSITION 1262
LOCATION
ALTITUDE
ORIENTATION
COMMUNICATION 1264
WIRED
NEAR FIELD
WIRELESS
BLUETOOTH
CELLULAR
WI-FI
1272
DEVICES 1270
1282
NETWORK 1280

Figure 12

DETERMINING A JOB GROUP STATUS BASED ON A RELATIONSHIP BETWEEN A GENERATION COUNTER VALUE AND A TICKET VALUE FOR SCHEDULING THE JOB GROUP FOR EXECUTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of and claims the benefit of priority under 35 U.S.C. §120 to U.S. patent application Ser. No. 15/192,309, filed on Jun. 24, 2016, which claims the benefit of priority to U.S. Provisional Patent Application Ser. No. 62/252,897, filed Nov. 9, 2015, each of which is herein incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to the field of computer operating systems and, more specifically, to job schedulers.

BACKGROUND

[0003] In computer operating systems and related software, a job scheduler (or "process scheduler") is an application that manages the distribution of work (e.g., in the form of jobs or processes) to different computing resources (e.g., processor cores). Current job schedulers have a performance loss when using multiple core systems. The loss of performance may be due to the use of operating system locks (e.g., mutexes), which are used to manage multiple cores accessing common data structures (e.g., concurrent data structures) and which put waiting threads to sleep. One such data structure is a job queue, which has producers of jobs (e.g., usually applications) on the input side and consumers of jobs (e.g., processor cores) on the output side of the queue. Inefficiencies can occur when multiple entities (e.g., multiple processors, processor cores, applications, or threads) try to simultaneously modify the shared queue data structure (e.g., because the locks only allow one entity to read/write to the structure at the same time, while all other entities must wait for access).

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Further features and advantages of the present disclosure will become apparent from the following detailed description, taken in combination with the appended drawings, in which:

[0005] FIG. **1** is a block diagram illustrating a conventional computing device in which a conventional job scheduler implements software memory locks;

[0006] FIG. **2** is a diagram of an example computing device that includes a job scheduler system (or just "job scheduler") as described herein;

[0007] FIG. **3**A illustrates operations associated with dequeuing job groups from the job group queue shown in FIG. **2**;

[0008] FIG. **3**B illustrates operations associated with stack operations associated with the execution stack shown in FIG. **2**;

[0009] FIG. **3**C illustrates operations associated with recycling job group containers from the job group queue shown in FIG. **2**;

[0010] FIG. **4** is a flow chart of a method for job scheduling as performed by the job scheduler that includes job stealing;

[0011] FIG. **5** is a diagram of the example device and job scheduler in example scenarios during operation;

[0012] FIG. **6** illustrates the state of the job scheduler at a later point in time, continuing the example of FIG. **5**;

[0013] FIG. **7** illustrates a steal operation for group A performed by the job scheduler, continuing the example of FIGS. **5-6**;

[0014] FIG. **8** illustrates a stealing of Group B operation, as caused by the stealing of Group A operation, continuing the example of FIGS. **5-7**;

[0015] FIG. **9** illustrates the job scheduler after Group C is finished on the stack, continuing the example of FIGS. **5-8**;

[0016] FIG. **10** illustrates the finishing of Group A, continuing the example of FIGS. **5-9**;

[0017] FIG. **11** is a block diagram illustrating an example software architecture, which may be used in conjunction with various hardware architectures herein described to provide a job scheduler system, which may be similar to the job scheduler shown in FIGS. **2** and **5-10**; and

[0018] FIG. **12** is a block diagram illustrating components of a machine, according to some example embodiments, configured to read instructions from a machine-readable medium (e.g., a machine-readable storage medium) and perform any one or more of the methodologies discussed herein.

[0019] It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION

[0020] The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. Numerous specific details are described to provide a thorough understanding of the present disclosure. However, in certain instances, details well known to those in the art are not described in order to avoid obscuring the description of the present disclosure.

[0021] Some operating systems use memory locking to prevent simultaneous access to a shared memory location (e.g., a data structure such as a job queue). An operating system memory lock (or just "lock"), such as a mutex or a semaphore, is a synchronization mechanism that may be used to manage access to the shared memory location for multiple actors (e.g., multiple threads of execution that each use the shared memory location). For example, a lock may be given by the operating system (OS) to an application thread (referred to herein simply as a thread) so that the thread can have exclusive access to the shared memory location (e.g., the data structure) until the thread is done using that memory location. Other threads that need access to this memory location may be denied access until the location is unlocked. Conventional lock-based systems incur performance loss since threads (e.g., processes, or applications) must wait and are often put to sleep until the memory location is unlocked in order to complete their work.

[0022] In accordance with an embodiment, a job scheduler system and method is described herein. The job scheduler system uses wait-free concurrent data structures along with atomic memory transactions to avoid or otherwise mitigate synchronization issues that cause inefficient processor activities such as waiting for memory locations to become

unlocked (e.g., using thread sleeping). Sleeping a process is relatively slow (e.g., on the order of milliseconds) as compared to atomic locks (e.g., on the order of a number of CPU cycles). The data structures include a job queue, an execution stack, and a job list stack. These data structures and associated atomic memory transactions described herein can render the processing of jobs more efficient, thereby improving the functioning of the computer itself.

[0023] FIG. **1** is a block diagram illustrating a conventional computing device **100** in which a conventional job scheduler **130** implements conventional operating system memory locking for portions of a memory **120** (e.g., including a data structure). The job scheduler **130** employs conventional software memory locks (e.g., mutexes), for example, to manage access by processors to a common memory location, such as an execution queue **124** stored in the memory **120**. The job scheduler **130** is identified herein by the data structure(s) used by the job scheduler for purposes of convenience, and is not otherwise separately identified.

[0024] The computing device **100** includes multiple central processing units (CPUs) **110**A, **110**B, **110**C, **110**D (collectively, CPUs **110**) (e.g., each having a single "core"). In other embodiments, the CPUs **110** may contain multiple cores, where each core may be thought of as a distinct CPU **110** for purposes of this disclosure. A communications bus **112** (e.g., a front-side bus, a back-side bus) communicatively couples the CPUs **110** to a memory **120** (e.g., random access memory (RAM) or cache memory).

[0025] During operation, job data **126** for a job (e.g., a running process) or a group of jobs from one of the CPUs **110** is added to an execution queue **124** to await execution. Threads from the CPUs **110** extract job data **128** from the queue **124** for execution. Worker cores of the CPUs **110** execute jobs sequentially off the end of the queue **124** until all the jobs on the queue **124** are complete (e.g., until the queue **124** is empty). With a conventional lock system ("OS Lock Mechanism") **122**, a thread needing a particular job in the queue **124** has to wait until that job comes to the end of the queue **124** before dequeuing it. The memory locks force CPUs **110** (and cores and threads) to wait for jobs to clear the execution queue **124**. For example, a thread may require a value from a computation from a job within the queue **124**, but that thread would have to wait for that computation to be pushed off the queue **124** and executed in a core in order to access the value of the computation returned from the core. In addition, conventional lock systems **122** may use locks that lock the entire queue data structure such that only one thread may have access at any given time and other threads may be forced to sleep while waiting.

[0026] Operating systems often use conventional job schedulers, such as the job scheduler **130**, which are capable of operating with jobs that do not explicitly expose dependencies because the OS should be compatible with applications that do not express dependencies for the jobs they send to the queue. These operating systems implement schedulers that attempt to mitigate dependencies using various known methodologies. These methodologies may be suitable for less-time-sensitive applications that have many large jobs. However, some software applications such as, for example, a game engine, may need to handle many small jobs which are time-sensitive (e.g., because the user is often waiting for a game to respond to their input). Conventional job schedulers may make working with many small, time-sensitive jobs less efficient because the latency of unlocking and waking (e.g., from sleeping) a thread can be much larger than the execution of the jobs within the thread. For example, the latency of unlocking a lock is many thousands of CPU cycles. As such, considerable processing power may be lost due to the lock based scheduling system, particularly when working with many small, time-sensitive jobs.

[0027] The job scheduler systems and methods described herein uses atomic memory transactions to reduce the number of required cycles to start the execution of a thread (e.g., to a few hundred cycles) and avoid at least some of the above identified technical problems with conventional job schedulers that employ waiting locks, thereby improving the functioning of the computer itself. For example, in some embodiments, all steps are done atomically, and the only waiting lock employed is a semaphore on which threads wait when there is no more work to do (e.g., when all data structures are empty). Unlike conventional schedulers that use conventional system locks, the systems and methods described herein allow threads to read/write to data structures at the same time (except for a few cycles during atomic operations).

[0028] Some known job schedulers use a method known as Earliest Deadline First (EDF). Under conventional EDF, the job scheduler has deadlines associated with jobs (e.g., when the result of each job will be needed). However, under some operational conditions such as with gaming engines, the gaming engine may be controlled by a user script such that the ordering of jobs is unpredictable and can change dramatically (e.g., from frame to frame, depending on behavior of the script). Known EDF schedulers are poorly equipped to handle such situations. The job scheduler and methods described herein are designed such that the order of evaluation is under the control of the user (e.g., the developer, or a game player). This enables the job scheduler to adapt itself dynamically (e.g., using job stealing).

[0029] Further, some known job schedulers use conventional Priority Queues (e.g., to alter when some jobs get executed over other jobs). One problem with conventional Priority Queues is that, when changing the priority of jobs, the job scheduler may need to lock the whole system (e.g., bringing everything to a stop) while reorganizing the queue and then starting threads over. The job scheduler and methods described herein may dynamically change the priorities (e.g., based on data usage) without having to freeze everything while maintaining the data structure.

[0030] FIG. **2** is a diagram of an example computing device **200** that includes a job scheduler system (or just "job scheduler") **230** as described herein. The computing device **200** includes multiple CPUs **210**A, **210**B, **210**C, and **210**D (collectively, "CPUs **210**") communicatively coupled to a memory **220** by a communications bus **212**. The CPUs **210** may be similar to the CPUs **110**, the bus **212** may be similar to the bus **112**, and the memory **220** may be similar to the memory **120**.

[0031] The job scheduler **230** includes several data structures stored and maintained in the memory **220**, including a job group queue **232**, an execution stack **236**, and a counter system (not shown). For purposes of convenience, the job scheduler **230** is identified herein by the collection of data structures used by the job scheduler (e.g., the job group queue **232** and the execution stack **236**), and is not otherwise separately identified. It should be understood that the job scheduler **230** may also include other logical and physical

components such as to enable the systems and methods described herein, which may include, but are not limited to, a separate processor or memory area, and a process or thread that periodically executes on one or more of the CPUs **210**.

[0032] The job group queue **232** may include one or more job groups (or just "groups") **242**, such as "Group A" through "Group N". Each group **242** includes an associated job list **244**, where each job list **244** identifies one or more jobs **246** of the associated group **242**. The execution stack (or just "stack") **236** includes jobs from one or more of the groups **242** (e.g., the jobs **246** from the job lists **244** associated with each group **242**, with each group **242** having one or more jobs **246**).

[0033] In the example embodiment, the scheduling system **230** is implemented as a state machine, wherein the scheduling system **230** is in only one state at a time and can transition between a finite number of states. In the example embodiment, the job scheduler **230** implements a wait-free (e.g., without traditional system locks that generate waiting processes) job stealing mechanism wherein a client (e.g., processor, game engine, application, thread, and so forth) can 'steal' jobs (e.g., job groups) from the queue **232**. The stolen job group **242** bypasses other jobs (e.g., other job groups **242**) ahead of it in the queue **232**, directly placing them on the execution stack **236** ahead of the jobs in the other job groups **242**. Further, the job scheduler **230** may also resolve dependencies of the stolen job group (e.g., stealing another job group **242** upon which the initial stolen job group **242** is dependent).

[0034] The term "stealing," as used herein, refers to reordering of a job or job group (e.g., the stolen job group) on a queue (e.g., changing the position of the stolen job group on the queue). In the example embodiment, stolen job groups are moved to the front of a job group queue (e.g., in front of any other pending job groups) and/or placed directly onto an execution stack (e.g., preparing the jobs for execution). Stealing, as described herein, differs from priority queues in multiple ways. For example, in some known priority queues, each job has a priority setting (e.g., often an integer), and the priority setting is used to identify a relative importance of the job to other jobs in the queue. When a job is picked to run off of the queue, the relative priority settings of all of the jobs on the queue may influence which job gets selected (e.g., the job with the highest priority setting on the queue may be selected). In contrast, stealing identifies a particular job and moves (e.g., reorders) that job within the queue immediately (e.g., initially regardless of any relative importance of the stolen job group to other job groups). Further, the stealing methods described herein enable the developer to in effect preempt the execution order of the stolen job group over all others currently on the queue. In contrast, under priority queues, the developer may change the priority setting, but this does not necessarily ensure that the prioritized job group moves immediately to the front of the queue (e.g., there may still be other jobs with higher priorities on the queue, or other jobs with the same priority that are ahead of the prioritized job in the queue).

[0035] In the example embodiment, the job scheduler **230** is lock-free (e.g., wait-free) in certain respects. In other words, the job scheduler **230** performs certain steps atomically, without the use of conventional waiting locks (e.g., locks, such as a semaphore, which block the execution of a thread requesting the lock until it is allowed access to the locked memory, usually by putting the thread to sleep). Particular operations are described herein as being executed atomically, such as incrementing and decrementing of certain counters associated with job stealing. This particular performance of steps atomically, as described herein, allows the job scheduler **230** to avoid use of waiting locks as they are commonly used by some conventional job schedulers. As such, during operation, threads are allowed concurrent access to key data structures (e.g., the job group queue **232**).

[0036] Jobs from a client (e.g., a CPU **210**, a game engine, an application, or the like) are typically packaged into groups (e.g., groups **242**) prior to being sent to the job scheduler **230**. Groups **242** are formed by packaging together multiple jobs (e.g., jobs **246** of the list **244**) that can run concurrently in any order (e.g., they have no dependencies with each other). Job groups **242** include a header and memory, including a job list structure (e.g., the associated list **244**). Each group **242** can be recycled using the header and memory location (e.g., referring to the act of reusing the same header and memory for a second set of jobs after a first set of jobs is finished executing). Recycling a job group **242** improves the efficiency of the job scheduler **230** since the creation (e.g., memory allocation) of a new job group would require an OS system call, and would incur an associated latency.

[0037] In some embodiments, the client can also add information (e.g., metadata) regarding any explicit dependencies for the packaged job group **242** (referred to herein as "dependent job group"). The dependencies for a particular job within a group specify which other job or jobs external to the group must be completed before the particular job can be executed (referred to herein as "dependency job" or "dependency job group"). In the example embodiment, each job group **242** may specify a single job- or job group-dependency (e.g., one-to-one, in which one job **246** or job group **242** must be executed before the referring group **242**). Multiple groups **242** may depend on the same group **242** (e.g., many-to-one). In other embodiments, each job group **242** may specify multiple dependencies (e.g., one-to-many). The term "dependent job group" is used herein to refer to a job group that is dependent upon another job or job group. The term "dependency job" or "dependency group" is used herein to refer to the job or job group upon which a dependent job group depends.

[0038] When a job group **242** is received by the job scheduler **230**, it is placed in the job group queue **232**. The queue **232** is a first in/first out (FIFO) style queuing data structure and algorithm (e.g., illustrated from left to right in FIG. **2**), although this queuing algorithm is modified as described herein (e.g., with stealing). The job scheduler **230** removes job groups **242** from the output side of the queue and resolves any dependencies before placing the jobs (e.g., from the associated job list **244**) on the execution stack **236**. The stack **236** is a last in/first out (LIFO) style data structure and algorithm, optionally modified as described herein. Jobs **246** are taken off the stack and executed by a processor **210**, after which they are marked as finished.

[0039] The counter system is used to help track the state of jobs **246**, including states such as queued, holding, stacked, executing, and finished. In some embodiments, the job scheduler **230** may use an atomic primitive called "compare-and-exchange," a memory transaction that will only update memory if the content has a specific value. This atomic primitive is subject to an issue distinguishing between equal values being stored at different times (e.g.,

the memory location starts with a first value written by a first thread, has the first value changed to a second value by a second thread, and then has the second value changed back to the first value by the second thread, which fools the first thread into thinking that nothing has changed when the first thread does the comparison—a problem known as the ABA problem in multithreading). To improve reliability, the job scheduler **230** uses counters on critical memory locations to distinguish between equal values being stored at different times by different threads. For example, when a critical memory location is successfully written to, the counter for that location is incremented to indicate the successful memory write. The counters may be used, for example, to help determine the state of a job and distinguish between equal values being stored at different times (e.g., the equal values would have different counter values).

[0040] In the example embodiment, each job group **242** includes at least two associated counters (not separately shown). A first counter is referred to herein as a "generation counter," storing a numerical value referred to herein as a "generation count." A second counter is referred to herein as a "job counter," storing a numerical value referred to herein as a "job count." The generation counter is used to track the state of the associated job group, and to help identify when the job group has been dequeued or stolen, is on the stack **236** or is waiting to get on the stack **236**, is executing, or is finished executing. The numerical value of the generation counter and/or whether the generation counter is even or odd may be used to distinguish between some of these different states. Once the job group has been dequeued and put on the stack, the job counter is used to track the number of jobs for the job group that remain on the stack (e.g., not yet executed).

[0041] When a job group container is first created (e.g., when memory is allocated for the container), the initial generation counter is set at an even number (the "starting generation count"). The exact numerical value of the starting generation count can be any arbitrary integer. The job scheduler is then free to place a received job group **242** (e.g., received from an application that wants the job group **242** to be executed) in the container and place the container on the job group queue **232**. The job scheduler **230** creates and transmits a ticket to the application that submitted the job group **242**. The ticket includes the memory location of the job group **242** (e.g., the memory location of the container for the job group **242**) and a "ticket value" at which the group will be considered finished (also referred to herein as the "finished generation count"). The finished generation count for a group may be, for example, the starting generation count+2. The ticket and the generation count are used to track the state of the job group **242** as it passes through the job scheduler **230**.

[0042] The state of a job group **242** and the value of the generation counter for that job group **242** may be linked to the ticket value for that job group. More specifically, when the generation counter is two less than the ticket value (e.g., generation counter=ticket value−2), then the job group **242** is in the queued state (e.g., the job group **242** is in the job group queue **232**). When the generation counter is one less than the ticket value (e.g., generation counter=ticket value−1), then the job group **242** is in the pushed state (e.g., the job group **242** has been dequeued or stolen and it is in one of three places: on the stack, waiting to get on the stack, or being executed by a CPU **210**). When the generation counter is equal to the ticket value (e.g., generation counter=ticket value), then the job group **242** is in the finished state (e.g., the job group **242** has left the stack and has been executed by a CPU). Accordingly, since the initial value of the generation counter is even, generation count values that are even numbered refer to job groups that are in the queue or finished executing, and generation count values that are odd numbered refer to job groups whose jobs are being executed, are in the stack, or are waiting to get onto the stack **236**.

[0043] Some known job schedulers have memory leak issues brought on by jobs that are scheduled but are never properly executed. The memory for these unexecuted jobs is never deallocated, and thus the amount of memory leaked can increase over time. These job schedulers must track pending jobs in order to avoid such memory leak issues. Here, the job scheduler **230** avoids or reduces such issues by reusing memory for jobs that come off the queue and are not properly executed. As such, the job scheduler **230** may not need to track job groups. If a job group **242** is incompletely executed, the scheduling system **230** may wait on it or, since job group containers are reused, a job group may be scheduled and then forgotten (e.g., not tracked).

[0044] In the example embodiment, there are several actions taken by the job scheduler **230** that include changing (e.g., incrementing) the generation counter. During a life cycle of the job group **242** container, the generation counter is incremented twice. First, it is incremented by one when the job group **242** is dequeued or stolen. Second, it is incremented by one when the job group **242** has completed execution. As such, when a job group container is recycled, the generation count for that container has been incremented by two each time (e.g., returning to an even value to start another cycle of use).

[0045] More specifically, when a job group is dequeued or stolen, the generation count is incremented by one to indicate that the associated job list **244** has been or will be put on the execution stack **236** (e.g., the generation count becomes odd after being dequeued or stolen, being used as a toggle switch). Only one thread will successfully steal or dequeue a job group **242** (e.g., the first thread to steal or dequeue it). Other threads may fail at dequeuing and stealing this job group **242** because they may detect that the generation count is not the expected value for a job group in the queue **232**, signaling that the job group **242** is no longer in the queue **232** (e.g., because it has already been dequeued or stolen). A job group **242** may only be stolen or dequeued if it is in the queue **232** and, accordingly, the expected generation count for dequeuing or stealing a job group may be the final generation count−2. If the generation count is not the ticket value−2, then another thread must have already dequeued or stolen the job group **242** and incremented the generation counter (e.g., so that the generation count may be the ticket value−1). An odd value of the generation counter also signals that the job group **242** has already been removed from the queue because of stealing or dequeuing and, accordingly, an odd value of the generation counter blocks a second thread from dequeing or stealing the job group **242**.

[0046] When a job group **242** has cleared the stack **236** and all of the jobs from the job group **242** have been completely executed, the job scheduler **230** increments the generation counter of that job group **242** by one (e.g., making the generation count even again). As such, the generation count has been incremented by two since the job group was put on the queue (e.g., once when dequeued/

stolen, and again when the group is finished). When the group **242** is finished, the generation count is equal to the ticket value of the group **242**, and any thread waiting on this particular group **242** (e.g., a dependent job group) will see the job group **242** as finished (e.g., by checking the generation count). As soon as a job group **242** is finished, any dependent jobs for that finished group **242** that were set to be rescheduled (e.g., held waiting to get on the stack **236** or put back on the queue **232** to be processed later) may then be safely placed on the stack **236**.

[0047] When an application thread needs the result from a specific job group with high priority, the thread issues a 'wait' on the specific job group, indicating that the result is required as soon as possible. If a wait is issued for a specific job group **242**, then the job scheduler **230** first checks the state of the job group **242** by comparing the generation count for the job group **242** with the ticket value for the same job group **242**. If the ticket value and the generation count are equal, then the job group **242** is finished, and the thread will take the output value of the executed job and return to the application that spawned the thread. If the ticket value is one greater than the generation count (e.g., the generation count is odd), then the job list **244** of the job group **242** is either on the execution stack **236** or waiting to be put on the stack **236** (e.g., "pushed"), or is currently being executed, and the job scheduler **230** may pick jobs from the stack **236** and execute them until the generation count of that job group **242** indicates that all of the jobs in the job list **244** for the job group **242** are finished and the thread will take the output value of the executed job and return to the application that spawned the thread. If the generation count is two less than the ticket value (e.g., the generation count is even and not equal to the ticket value), then the job group **242** is still in the queue, and the job scheduler **230** may go through the entire stealing and dependency resolving process for that job group **242** first, then pick jobs to execute from the execution stack until the generation count of the job group **242** indicates that it is finished.

[0048] The job counter for the job group **242** keeps track of the number of completed jobs within the group **242** (e.g., the associated job list **244**). Each job group **242** includes one or more jobs for execution, and the job counter is used to determine when the last job is executed for the group **242**. The job counter is initialized to the number of jobs contained within the job group **242** when the job group **242** is first placed in a container, and gets atomically decremented every time a job that belongs to the group **242** has finished executing. When the job counter gets to zero, the group **242** is finished executing, and the generation counter is atomically incremented to tag the group as finished. Accordingly, after the group **242** is finished, the dependent jobs of that group **242** are added to the execution stack (e.g., if any exist).

[0049] In some known lock-free systems, issues may develop with respect to dependency chains. Jobs put on the execution stack can execute concurrently (e.g., many threads can pop jobs and execute then at the same time) and therefore, in some situations, it is not possible for a thread waiting on a specific ticket to execute anything from the stack except for jobs from the current job groups on the stack. As such, those systems can, in some situations, behave as a one core system, with all cores waiting on a single core to do all the work. Accordingly, the job scheduler **230** described herein implements at least the counter system and uses job lists to mitigate these scenarios.

[0050] Referring again to FIG. **2**, the job lists **244** hold the list of jobs that belong to a group **242** while the group **242** is in the queue **232** (e.g., when not stolen). Additionally, when the group **242** moves to the stack **236** to be executed, the job list **244** holds the list of jobs that are to be rescheduled (e.g., the dependent jobs of the group **242**) while the group is executing.

[0051] The job scheduler **230** creates, uses, and recycles job lists **244**. For example, when the job group **242** is removed from the queue **232** and put on the stack **236** for execution, the associated job list **244** is used to hold secondary job groups (e.g., dependent jobs **246** from dependent job groups **242** that are dependent on the removed job group) from entering the stack while the removed job group executes. Use and recycling of job lists **244** is described in greater detail below. The efficient use of the job lists **244** is made possible by the generation counter (e.g., as a toggle switch). In the example embodiment, the generation counter includes a numerical value (e.g., an integer). As used herein, the term "generation counter" may be used, in some contexts, to refer to the numerical value. For example, when the generation counter for a particular job group **242** is even, the associated job list **244** contains jobs **246** that belong to a first job group (e.g., the removed job group). When the generation counter is odd, the job list **244** contains dependent jobs for that removed job group that will need to be put on the stack **236** when the removed job group **242** is finished executing. The combination of the job list **244** and the generation counter allows the delayed insertion of a set of jobs on the stack **236** on a per-group basis, which allows for dependent jobs to be dealt with in a very efficient way.

[0052] The job scheduler **230** may "recycle" the memory regions associated with job groups **242** in the queue **232**, job lists **244**, and/or job groups **242** in the execution stack **236**. The jobs within the job lists **244** go on the stack for execution. A job group **242** (e.g., a job group container) is empty when it is recycled. During operation, memory regions may be allocated and deallocated (e.g., "malloc( )" and "free( )", respectively, in C) by the job scheduler **230** for various purposes (e.g., creating new job groups **242** or job lists **244**). As used herein, the term "recycling" refers to the act of maintaining an already-allocated memory region after it has been unassigned (e.g., after a first purpose has been satisfied), then reassigning that memory region to a new purpose. In other words, a "recycled" memory region is not deallocated once its first purpose is satisfied and, thus, recycling avoids calling the operating system for a new memory allocation. For example, when a job group **242** is dequeued, the memory region within the job group queue **232** may be recycled. Instead of deallocating the memory region when the job group is dequeued, the memory region is maintained and tracked by the job scheduler **230**. When a new job group **242** enters the queue **232**, that already-allocated memory region may be assigned to the new job group. As such, with recycling of memory regions, the job scheduler does not expend the computational resources to deallocate and reallocate memory. Unused job groups are tracked and maintained by the job scheduler **230** in a distinct pool (e.g., a "recycling stack").

[0053] In the example embodiment, generation counters persist and stay with their job group containers through recycling. The generation counter is recycled with the

recycled container and maintains the same value through recycling (e.g., an even integer equal to the previous group's ending generation count). Accordingly, the starting generation count for a group that is assigned to a recycled group container is whatever number comes through recycling (i.e., the previous group's ending generation count).

[0054] To facilitate memory recycling and speed of processing, the job scheduler **230** may implement one or more of the queue **232**, the job lists **244**, and the stack **236** as linked lists. Linked lists enable the job scheduler **230** to easily add and remove elements from the list dynamically, either with newly allocated memory (e.g., when first creating the job groups **242**) or with pre-allocated, recycled memory regions. Memory may be added as needed, but once allocated, the memory is maintained (e.g., not deallocated) and may be recycled to reduce the computational burden for managing the queue **232**, job lists **244**, and/or the stack **236**. Job groups **242**, job lists **244**, and the stack **236** may be implemented as simple data structures (e.g., using "struct" in C# or C++) containing data, along with a pointer to the next structure, thereby establishing a linked list. For example, a job group **242** may include a pointer to the next job group **242** in the queue **232**, and may also include another pointer to the associated job list **244**.

[0055] During operation, in the example embodiment, when the job scheduler system **230** starts, it creates a number of worker threads (e.g., typically equal to the number of cores) and leaves one core for the main application thread. The worker threads loop in the following way: (1) check if anything can be executed on the stack **236**, and if so, execute it; (2) if there is nothing to execute on the stack **236**, then check if anything is in the queue **232**. If there is, then dequeue the next group **242**, resolve the group's dependencies, and check the stack again **236**; and (3) if nothing is available on the stack **236** or the queue **232**, then the thread goes to sleep. Threads are awoken when new jobs are scheduled.

[0056] FIGS. **3**A-**3**C each display sections of a flow chart illustrating an example method **300** for job scheduling, as performed by the job scheduler **230**, that does not include stealing. FIG. **3**A illustrates operations associated with dequeuing job groups **242** from the job group queue **232**. FIG. **3**B illustrates operations associated with the execution stack **236**. FIG. **3**C illustrates operations associated with recycling job group containers from the job group queue **232**.

[0057] Referring now to FIG. **3**A, in the example embodiment, at operation **310**, the job scheduler **230** checks whether there are jobs (e.g., job groups **242**) in the job group queue **232**. If no job groups are available to be dequeued, the job scheduler **230** sleeps at operation **312**, cycling back to test again later. If one or more job groups **242** are available for dequeuing from the job group queue **232**, the job scheduler **230** dequeues a job group **242** from the job group queue **232** at operation **314**. If it is determined at operation **316** that the dequeued job group **242** is empty (e.g., because the group contents were stolen while it was on the queue), that job group **242** is flagged for recycling at operation **318**. Recycling of job group containers is described in greater detail below (e.g., see FIG. **3**C).

[0058] If, at operation **316**, the job group **242** is not empty, the job scheduler **230** atomically increments a generation counter associated with the job group **242** at operation **320**. In the example embodiment, incrementing operations performed on the generation counter are performed atomically (e.g., the dequeuing and incrementing happen as one), thereby avoiding some concurrent operation situations (e.g., another thread trying to dequeue the same group, but prior to the generation counter being incremented). The job scheduler **230** extracts the job list **244** associated with the job group **242** at operation **322**, as well as dependency information for the dequeued job group **242** (e.g., whether the dequeued job group depends upon any other job or job group). If, at operation **324**, the dequeued job group **242** is not a dependent job group, then the jobs (e.g., from the associated job list **244**) for that job group **242** are pushed onto the stack **236** for execution at operation **326**, and the job scheduler **230** loops back to operation **310** to check for additional job groups.

[0059] If, at operation **324**, the dequeued job group **242** is a dependent job group (e.g., identifies one or more dependency groups), then the job scheduler **230** checks the state of the dependency group at operation **328** (e.g., by checking the generation counter for the dependency group). In the example embodiment, each job group **242** may identify at most one dependency group. If, at operation **330**, the dependency group is finished (e.g., all jobs from that job group are finished executing), then the jobs (e.g., from the associated job list **244**) for the dependent job group **242** are pushed onto the stack **236** for execution (e.g., see operation **326**), and the job scheduler **230** loops back to operation **310** to check for additional job groups. If, at operation **330**, the dependency group is not yet finished (e.g., has unexecuted jobs on the stack **236**, or is itself still in the job group queue **232** waiting to get on the stack **236**), then the job scheduler **230** holds the dependent job group **242** at operation **332** (e.g., re-checks again later, looping to operation **328**) until the dependency group is finished. Once the dependency group is found to be finished at operation **330**, the job scheduler **230** pushes the jobs for the dependent job group **242** onto the stack **236** for execution and the job scheduler **230** loops back to operation **310** to check for additional job groups.

[0060] Referring now to FIG. **3**B, the job scheduler **230** manages the stack **236**. More specifically, in the example embodiment, the job scheduler **230** checks whether there are jobs on the stack **236** ready for execution at operation **334**. If there are no jobs on the stack **236**, the job scheduler returns to the dequeuing process shown and described above in reference to FIG. **3**A (e.g., to operation **310**). If there are jobs on the stack **236**, the job scheduler **230** pops a job from the stack and sends the job for execution (e.g., to one of the CPUs **210**) at operation **336**. On completion of the job, the result is sent to the requesting client at operation **338** and the job scheduler **230** atomically decrements a job counter **340** (e.g., atomically) at operation **340** for the job group **242** associated with that job. At operation **342**, if the job counter for that job group **242** is not zero (e.g., if there are still jobs for that job group on the stack **236**), then the job scheduler cycles to pop another job from the stack **236** (e.g., at operation **336**). In the example embodiment, the job scheduler **230** does not have to wait (e.g., between operation **336** and operation **338**) for the job to be executed and the result returned. The job scheduler **230** may concurrently send multiple jobs from the stack **236** for execution.

[0061] If the job counter for the job group **242** is zero, then the job scheduler **230** atomically increments a generation counter for that job group **242** at operation **344** and notifies the client that the job group **242** is finished at operation **346**.

If a dependent job group was waiting on the completed job group **242** (e.g., if the completed job group is a dependency group) at operation **348**, then the jobs from the dependent job group are loaded onto the stack **236** at operation **350** and are processed (e.g., cycling to operation **336**). If the completed job group **242** is not a dependency group, then the job scheduler **230** cycles to check for more jobs on the stack **236** (e.g., cycling to operation **334**).

[0062] Referring now to FIG. **3**C, the job scheduler **230** recycles job group containers (e.g., the memory region of an empty, completed job group **242**). More specifically, in the example embodiment, the job scheduler **230** checks the state of the job group container at operation **352**. If, at operation **354**, the associated job group **242** is not finished, then the container is held at operation **356**, and the job scheduler cycles to operation **352**. If the job group is finished, then the job scheduler **230** puts the job group container on a recycling stack for later reuse at operation **358**.

[0063] In the example embodiment, the processes involved in dequeuing the jobs as shown in FIG. **3**A, the process involved in stack operations as shown in FIG. **3**B, and the process involved in recycling as shown in FIG. **3**C may occur concurrently, excepting the atomic operations described above. In other words, the processes shown in FIGS. **3**A-**3**C may be interleaved such as to all be happening at the same time.

[0064] FIG. **4** is a flowchart of a method **400** for job scheduling as performed by the job scheduler **230** that includes job stealing. Job stealing involves preempting the order of the job groups **242** in the job group queue **232**. At operation **410**, the job scheduler **230** receives a request associated with Job X (e.g., a request for the value of a calculation that results from the execution of Job X). The request, for example, may originate from a software application such as a game engine, perhaps in response to an action from a user (e.g., via an application thread associated with the game engine). As used herein, the term "client" is used to refer to the requesting application (e.g., game engine), process, thread, or CPU.

[0065] At operation **412**, the job scheduler **230** determines the state of Job X (e.g., of the job group **242** containing Job X). In the example embodiment, the job scheduler **230** performs operation **412** using the generation counter for the job group **242** and the finished generation count (e.g., from the ticket). The states available for a job group **242** include: "Queued" (e.g., in the queue **232**), "Pushed" (e.g., being executed by a CPU **210**, on the stack **236**, or waiting to get on the stack **236**), or "Finished" (e.g., execution completed). Some of these states may be distinguished from others using the generation counter and/or the job counter. If, at operation **413**, the state of the job group **242** is Finished (e.g., if the generation counter equals the finished generation count), then the result of the job is available (e.g., because the job's execution is complete) and the result is returned to the client via the client thread at operation **414**. If, at operation **413**, the state of Job X is Pushed (e.g., if the generation counter is odd, or if the generation counter equals one less than the finished generation count), then Job X is already on the stack **236** or is waiting to get on the stack **236** and, as such, the job scheduler **230**, at operation **416**, pops jobs off the stack and executes those jobs until Job X is Finished. When Job X is finished (e.g., finished executing within a core), the result of the job is available, and the job scheduler **230** returns the result to the client via the client thread at operation **414**.

[0066] If, at operation **413**, the state of Job X is Queued (e.g., if the generation counter is even and not equal to the finished generation count, or if the generation counter is two less than the finished generation count), then the job scheduler **230** extracts ("steals") the job group **242** containing Job X from the queue **232** at operation **420**. Stealing a job includes at least several steps. First, at operation **422**, the job scheduler **230** atomically increments the generation counter for the job group **242** (e.g., making the generation counter odd and making the generation counter equal to one less than the finished generation count, signifying that the job group has been stolen). In the example embodiment, operations **420** and **422** are performed atomically. In some embodiments, operations **420** and **422** may be combined into a single atomic operation. The job scheduler **230** then removes the job list **244** of the job group **242** in the queue **232** at operation **424**, leaving the group container in the queue (e.g., with an empty job list **244** containing only a null pointer). At operation **426**, the job scheduler **230** extracts job list data from the associated job list **244**, leaving an empty job list **244** (e.g., a single element containing a null pointer).

[0067] The job scheduler **230** then analyzes the dependency data for the job group **242** to determine all dependencies for all the jobs in that job group **242** at operation **428**. The dependency data specifies, or can be used to determine, which secondary jobs (e.g., which other job groups **242**) must be executed prior to the execution of the stolen job (e.g., the job group **242** including Job X).

[0068] If, at operation **429**, no dependencies are specified within the dependency data, or if there is no dependency data, then the job scheduler **230** pushes all of the stolen jobs (e.g., all of the jobs from the job list **244** associated with the stolen job group **242**) onto the stack **236** at operation **430**. Since there are no dependency conflicts prior to placement of jobs **244** of the stolen job group **242** on the execution stack, the jobs can safely be executed (e.g., in any order, and thus can be processed by any thread with any core). In some embodiments, each job group **242** is packaged such that the jobs within the group **242** do not depend on each other (e.g., they can be executed in any order), and each group depends on at most one other group. In other embodiments, each job group can depend on multiple other job groups **242**.

[0069] If, at operation **429**, the stolen job group **242** includes one or more specified dependencies, then for each dependency group (e.g., dependency group Y_i, where i=1 . . . N, and where N is the number dependencies), the job scheduler **230** determines the state of the dependency Y_i at operation **432**. In the example embodiment, each job group **242** includes at most one dependency group, Y. The dependency group Y refers to a specific dependency job group **242** for the job group **242** containing Job X. The dependency group Y may be in any state mentioned above (e.g., Queued, Pushed, or Finished). The simplest case is if a dependency group Y is already executed (e.g., "Finished") at operation **433**. In this case, the job scheduler **230** pushes the jobs from the stolen job group **242** directly onto the execution stack **236** at operation **430** and ends, thereby completing the steal of the job group **242**.

[0070] If, at operation **433**, the dependency group Y is in the pushed state (e.g., is already on the stack **236**), then the job scheduler **230** holds the dependent job group, at operation **434**, until the jobs clear the stack **236** prior to pushing the stolen job group **242** containing Job X onto the stack **236** at operation **430**. If, at operation **433**, the dependency group

Y is still in the queued state (e.g., in the job group queue **232**), then the job scheduler **230** holds the stolen job group **242** from entering the stack **236** at operation **436** and resolves the dependency group Y (e.g., recursively cycle to operation **420**, initiating a steal operation on the dependency group Y) at operation **438**. In other words, the initial stolen job group **242** is not put on the execution stack **236** until the job scheduler **230** steals the dependency group Y from the queue **232**, resolves any of its dependencies (e.g., recursively), and then places them on the stack **236** so that they can be executed. After the dependencies are executed on the stack **236**, then the job scheduler waits for those dependent jobs to clear the stack at operation **434** before pushing the jobs from the stolen job group **242** onto the stack **236** at operation **430**.

[0071] In some embodiments, the processes executing the method **400** shown in FIG. **4** may execute concurrently with the processes executing the method **300** shown in FIGS. **3**A-**3**C, excepting the atomic operations described above. In some embodiments, any or all of the operations shown in methods **300**, **400** are performed atomically. In some embodiments, some operations are combined into a single atomic operation. For example, in some embodiments, operations **420** and **422** may be combined into a single atomic operation. In other embodiments, operations **412**/**413**, **420**, and **422** may be combined into a single atomic operation. In some of these embodiments, operation **424** may also be included in the combined atomic operation.

[0072] In some scenarios, it may be possible for multiple threads to attempt to steal the same job group from the queue **232**. For example, a first thread and a second thread may attempt to steal a job group, and may both test the state of the job group (e.g., operations **412**/**413**) at a time when the job group is still available to steal (e.g., before either thread executes atomic operation **420**/**422**). In one example embodiment, until one of the two threads actually performs operations **420**/**422** (e.g., atomically), either of the two threads may initiate operations **420**/**422**. The first thread to execute operations **420**/**422** effectively makes the job group unavailable to steal to the other thread. For example, presume both threads test the state of the job group at operations **412**/**413**, and both threads see the job group as available to steal. Subsequently, both threads are going to attempt to steal the job group, because both have tested and determined that the job group is available to steal. The first thread is the first to atomically execute operations **420**/**422**, thereby succeeding in the steal (e.g., moving the job list for the stolen job group to the execution stack **236** and emptying the job group). The second thread then attempts to steal the job group and fails (e.g., at operation **420**) because the job group is no longer available to steal (e.g., because the job group is now empty). As such, the first thread succeeds in the steal and the second thread fails its steal attempt.

[0073] FIGS. **5** to **10** depict the example device **200** and job scheduler **230** in example scenarios during operation. As shown in the example scenario of FIG. **5**, the job group queue **232** includes multiple job groups **512** awaiting execution (e.g., "Group A" **512**A, "Group N" **512**N, "Group B" **512**B, "Group C" **512**C, and "Group D" **512**D). Each job group **512** in the job group queue **232** has an associated job list **514** (e.g., "List A" **514**A, "List N" **514**N, "List B" **514**B, "List C" **514**C, and "List D" **514**D, respectively). For example, in the context of graphics processing for a game engine, Group D **514**D may compute the position of many virtual characters, Group C **514**C may perform collision detection on those characters, Group B **514**B may recompute new positions in response to collisions according to a gaming physics, and Group A **514**A may prepare the whole scene for rendering on the GPU. As such, Group A **514**A may depend on Group B **514**B, Group B **514**B may depend on Group C **514**C, and Group C **514**C may depend upon Group D **514**D.

[0074] In the example embodiment, another job group **5120**, "Group O," along with an associated job list **5140**, "List O," is passed to the job scheduler **230** (e.g., from one of the CPUs **210**) for addition to the job group queue **232**. The job groups **512** may be similar to the job groups **242**, and the job lists **514** may be similar to the job lists **244**. While the job lists **244**, **514** are shown in FIGS. **2** and **5**-**10** separately from the job groups **242**, **512** for purposes of illustration, in some embodiments, the job lists **244**, **514** may be integrated into or within the job groups **242**, **512** themselves.

[0075] The execution stack **236** includes two groups, "Group U" **512**U and "Group Y" **512**Y, each having multiple jobs **246** (e.g., jobs from their associated job lists **514**, illustrated in FIG. **5** as "U1," "U2," and "Y1" through "Yn"). It should be understood that the jobs **246** are illustrated on the execution stack **236** in FIGS. **2** and **5**-**10** grouped together for purposes of description, but, as mentioned above, the execution stack **236** is a LIFO structure and, as such, the queue is an ordered set of jobs (e.g., each of the jobs from the illustrated groups), where the top-most group in the stack **236** represents the top-most jobs. The jobs on the stack **236** are handled as individual jobs. In other words, they may be picked up by different threads and may be sent to different processors for execution. The job scheduler **230** may track the jobs of a particular job group **242** (e.g., with the job counter and generation counter).

[0076] In this example, though not illustrated in FIG. **5**, Group A **512**A has 100 jobs, Group B **512**B has 1 job, Group C **512**C has 50 jobs, and Group D **512**D has 1 job. Further, Groups A-D **512**A-**512**D also include interdependencies. More specifically, the dependencies of the four job groups are as follows: Group A **512**A depends on Group B **512**B, Group B **512**B depends on Group C **512**C, and Group C **512**C depends on Group D **512**D. The scheduling order is illustrated from right to left within the job group queue **232** as shown in FIG. **5**. As such, Group D **512**D is scheduled, followed by some unidentified groups, then Group C **512**C, followed by other unidentified groups, then Group B **512**B, Group N **512**N, and Group A **512**A. Each of these scheduled groups will proceed according to the above order unless that scheduling order is interrupted, for example, by a call to steal one of the four groups (e.g., if there is a call or a 'wait' for a value resulting from the execution of one of these groups which necessitates a steal).

[0077] Further, jobs for a "Group L" **512**L are being sent from the stack **236** to the bus **212** (e.g., for execution on one of the CPUs **210**). It should be understood that jobs from the stack **236** are sent to the bus **212** for execution individually, and are illustrated as grouped in these examples for ease of discussion.

[0078] Continuing the example, FIG. **6** illustrates the state of the job scheduler **230** at a later point in time. Here, "Group O" **5120** has been added to the job group queue **232**, and an application (the client, e.g., the user script of a game) requires the resulting value of the execution of Group A

512A. The application signals the requirement by issuing a "wait" on the A group 512A in the job scheduling system (e.g., with the job scheduler 230).

[0079] At this point in time, Group A 512A and Group B 512B are in the queue 232 as shown, jobs from Group C 512C are on the execution stack 236, and Group D 512D is finished. When Group C 512C was moved from the queue 232 to the execution stack 236, the group container 610 for Group C 512C (e.g., the memory being used by Group C 512C while on the queue 232) was emptied, and may be recycled once all associated jobs are completed. Further, because the jobs 514C for Group C 512C were moved to the stack 236, the associated job list 612 for Group C 512C is emptied (e.g., jobs C1 to C50 have moved to the stack 236 and the job list 514C contains a null pointer), but the job group container 610 is maintained and used while the jobs 514C for Group C 512C (e.g., jobs C1, C2, . . . , C50) are on the stack 236. Once the jobs 514C are finished on the stack 236, the job scheduler 230 will check the job list 612 for Group C 512C (e.g., until empty). If the job list 612 contains another list (e.g., one or more additional jobs, such as from job groups dependent on Group C 512C, added as described below), then this additional list of jobs 514C is also placed on the stack 236 for execution. When the job list 612 is determined to be empty, then it will be recycled along with the empty group container 610. In other words, the job scheduler 230 maintains the job group container 610 (e.g., for Group C 512C) until it is determined that all jobs associated with that group have completed (e.g., including all dependent jobs).

[0080] FIG. 7 illustrates a steal operation 720 for group A 512A performed by the job scheduler 230. Continuing the example, receipt of the "wait" on Group A 512A triggers the steal operation 720 for Group A 512A. Presume that, at the time the steal operation 720 is initiated, the generation counter for group A is set to 100, the generation counter for group B is set to 200, and the generation counter for C is set to 301 (e.g., because it is on the stack). Accordingly, the ticket value for group A is 102, the ticket value for group B is 202, and the ticket value for group C is 302 since the ticket value is equal to the initial generation counter value+2. The steal operation 720 will proceed if Group A 512A is still in the queue 232 and no other thread has stolen it, such as shown in FIG. 7 (e.g., see also operation 412). In other situations, the steal attempt would fail if, for example, another thread has already stolen Group A 512A, or if Group A 512A had moved off the job group queue 232 and onto the execution stack 236 (e.g., if the generation counter for the job group is odd, or not equal to the ticket value−2).

[0081] Returning to the example shown here, the stealing operation 720 of Group A 512A starts with the removal of the Group A 512A data from a Group A container 710 on the queue 232, including the removal of the group A job list 514A data. If Group A 512A is stolen successfully, the job scheduler 230 atomically increments the generation counter for Group A 512A by one (e.g., from 100 to 101). Since, in this example, Group A 512A depends on Group B 512B, which is still in the queue 232 at the time Group A was stolen, the job scheduler 230 cannot put the job list for Group A 512A on the stack. As such, the job scheduler 230 attempts to steal Group B 512B in order to resolve the dependency for Group A 512A. Since Group A 512A depends on Group B 512B, the job list data for group A (e.g., List A 514A) is moved to the back of the job list for Group B 512B (e.g., List B 514B) after Group B has been stolen so that the jobs of List A 514A can be executed after the jobs in Group B 512B. Moving the job list for Group A 512A at the back of the job list for Group B 512B (e.g., List B 514B, as illustrated by broken line 722) may be implemented, for example, by linking the tail of the linked list for List B 514B to the head of the linked list for List A 514A.

[0082] At this point, a job list 712 for Group A 512A is empty, and so is the job group container 710 for group A 512A in the queue 232. The job list 712 and the job group container 710 may be recycled once the job group container 712 has dequeued and the associated job list has been emptied of all dependent jobs and job lists.

[0083] Continuing the example, FIG. 8 illustrates a stealing of Group B operation 820, in reaction to the stealing of Group A operation 720. In this example, the stealing of Group B 512B is successful and, as such, the system increments the counter for Group B 512B by 1 (e.g., from 200 to 201). Since Group B 512B depends on Group C 512C, the job scheduler 230 tries to steal Group C 512C (not depicted), which fails because the jobs from Group C 512C are already on the execution stack 236 (e.g., see operation 416). More specifically, the steal of Group C 512C fails because the Group C container 610 is empty, and the generation counter for Group C 512C is odd (and the generation counter=ticket value−1), signaling that it is in the pushed state and is no longer on the queue. Group C 512C was previously added to the stack 236 because Group C 512C depends on Group D 512D, and Group D 512D is finished, thus making it safe to put Group C 512C on the stack 236. It should be noted that the placement of Group C 512C on the stack 236 is not directly shown in a figure, but occurred between the actions depicted in FIG. 5 and FIG. 6.

[0084] At this point, the execution of Group C 512C is not yet complete. As such, the job scheduler 230 pushes Group B 512B (e.g., the job list B 514B) to the back of the job list for Group C (e.g., job list container 612, "Empty List C"), as illustrated by the broken line 822. This is possible because Group C 512C has not yet completed execution, and the job list for Group C 512C (e.g., job list container 612) has not been recycled.

[0085] During operation, one or more threads start to pop jobs from the stack 236 (e.g., jobs 514C, "C1"-"C50") and execute them. The job counter for Group C 512C initially starts at 50 (e.g., since Group C 512C has 50 jobs). For each job executed from Group C 512C, the job counter is atomically decremented by 1. When all the jobs 514C on the stack 236 are complete for Group C 512C, the job counter for Group C 512C reaches zero, and the generation count for Group C is atomically incremented by 1 to 302.

[0086] FIG. 9 illustrates the job scheduler 230 after the jobs for Group C 512C are finished on the stack 236. Continuing the example, when the last of the Group C jobs 514C are finished (e.g., taken from the stack 236 and executed by a CPU), Group C 512C is marked as done by atomically incrementing the generation counter for Group C 512C by one, thereby making the generation counter match the ticket value. The job scheduler 230 checks the job list for Group C (e.g., the job list 612) for additional jobs and finds the job list for Group B (e.g., List B 514B), as illustrated in FIG. 8. List B 514B is put on the execution stack 236. The job scheduler 230 determines that the job list 612 is now empty and, as such, the job list 612 and job group container 610 for Group C 514C are recycled.

[0087] In this example, the job list **514**B for Group B **512**B has a single job, "B1," now at the head of the stack **236**. As such, the first thread to execute that job will cause the job scheduler **230** to atomically increment the generation count for Group B **512**B to **202** (e.g., marking it as finished since the generation count=the ticket value).

[0088] FIG. **10** illustrates the finishing of Group A **512**A. Since all of the jobs in the job list **514**B are now finished, the job scheduler **230** then checks a job list **812** for Group B **514**B for jobs that depend on Group B **512**B and finds the job list **514**A for Group A **512**A, as illustrated in FIG. **9**. The job scheduler **230** then pushes the job list **514**A onto the stack **236** and recycles the job list **812** and a job container **810** for Group B **512**B. Threads pop jobs from the job list **514**A (e.g., from the stack **236**) and, after each job is completed, atomically decrement the job counter for Group A **512**A until all of the jobs in the job list **514**A complete execution and the job counter reaches zero. When Group A **512**A is finished, the generation count for Group A is atomically incremented by one (e.g., to 102), thereby marking Group A **512**A as finished since the generation counter is equal to the ticket value. The job scheduler **230** then checks the job list **712** for Group A **514**A, finds no additional jobs, and subsequently recycles the job list **712** and job group container **710**.

[0089] At this point, the client thread that issued the wait on Group A **512**A detects that it has finished (e.g., because the ticket value of 102 for Group A matches the generation count of 102 for Group A **512**A). As such, it will return to the application with the value from the execution of Group A **512**A.

[0090] The example shown in FIGS. **5** to **10** illustrate a simple dependency chain. In some embodiments, it is possible that another group or groups (e.g., Group E, not shown) may also depend on Group B **512**B, Group C **512**C, or Group D **512**D. As such, the Group E job list may get added to the job list for group B, group C, or group D to be scheduled when their respective lists are finished. Accordingly, the job scheduler **230** may scale to any number of jobs and dependencies.

[0091] For example, consider the following example with groups including job lists implemented as linked lists, whereby two groups each depend upon a third group. In this example, a Group G1 includes jobs X, Y, and Z (annotated as G1(X-Y-Z), where dashes indicate the linked order with the last job unlinked to another), a Group G2 includes jobs D, E, F, G, and H (i.e., G2(D-E-F-G-H)), and a Group G3 includes jobs A, B, and C (i.e., G3(A-B-C)). Further, Groups G2 and G3 both depend on G1. In this example, Group G1 is dequeued first, and its jobs are put on the stack **236**. As such, the G1 job list is empty, and its generation count is odd. As part of this example, while the G1 job list is still on the stack **236**, Group G2 is then dequeued. Since G2's dependency (e.g., G1) is still on the stack **236**, the G2 jobs (D-E-F-G-H) are added to the G1 job list, which was emptied when all of the G1 jobs were put on the stack **236**). Further, while the G1 job list is still on the stack **236**, Group G3 is then dequeued. As such, the G3 jobs (A-B-C) are also added to G1's job list (e.g., linked to the end), resulting in the linked list (D-E-F-G-H-A-B-C). When the original G1 jobs are finished, the scheduler **230** retrieves the jobs (D-E-F-G-H-A-B-C) from the G1 job list and places them on the stack **236**. Note that because each group has no internal dependencies, and G2 does not depend on G3, the ordering of the list does not matter in this example, allowing the G2 list to be appended to the end of the G3 list, or vice versa. In other words, once the G1 jobs are complete, any of the jobs A, B, C, D, E, F, G, H may be safely executed in any order.

[0092] Further, the job scheduler **230** and devices **200** described herein may include multiple cores adding jobs to the queue **232** simultaneously, while at the same time there may be multiple cores executing jobs simultaneously. The combination of the queue **232**, the stack **236**, the counting system, and the stealing mechanism described herein lead to better performance and more reliability than existing lock-free solutions, which constitutes an improvement to the functioning of the computer itself.

[0093] The detailed examples of how to use a job scheduling system, according to the disclosure, are presented herein for illustration of the disclosure and its benefits. Such examples of use should not be construed to be limitations on the logical process embodiments of the disclosure, nor should variations of user interface methods from those described herein be considered outside the scope of the present disclosure.

[0094] Certain embodiments are described herein as including logic or a number of components, modules, or mechanisms. Modules may constitute either software modules (e.g., code embodied on a machine-readable medium or in a transmission signal) or hardware modules. A "hardware module" is a tangible unit capable of performing certain operations and may be configured or arranged in a certain physical manner. In various example embodiments, one or more computer systems (e.g., a standalone computer system, a client computer system, or a server computer system) or one or more hardware modules of a computer system (e.g., a processor or a group of processors) may be configured by software (e.g., an application or application portion) as a hardware module that operates to perform certain operations as described herein.

[0095] In some embodiments, a hardware module may be implemented mechanically, electronically, or with any suitable combination thereof. For example, a hardware module may include dedicated circuitry or logic that is permanently configured to perform certain operations. For example, a hardware module may be a special-purpose processor, such as a field-programmable gate array (FPGA) or an Application Specific Integrated Circuit (ASIC). A hardware module may also include programmable logic or circuitry that is temporarily configured by software to perform certain operations. For example, a hardware module may include software encompassed within a general-purpose processor or other programmable processor. It will be appreciated that the decision to implement a hardware module mechanically, in dedicated and permanently configured circuitry, or in temporarily configured circuitry (e.g., configured by software) may be driven by cost and time considerations.

[0096] Accordingly, the phrase "hardware module" should be understood to encompass a tangible entity, be that an entity that is physically constructed, permanently configured (e.g., hardwired), or temporarily configured (e.g., programmed) to operate in a certain manner or to perform certain operations described herein. As used herein, "hardware-implemented module" refers to a hardware module. Considering embodiments in which hardware modules are temporarily configured (e.g., programmed), each of the hardware modules need not be configured or instantiated at

any one instance in time. For example, where a hardware module comprises a general-purpose processor configured by software to become a special-purpose processor, the general-purpose processor may be configured as respectively different special-purpose processors (e.g., comprising different hardware modules) at different times. Software may accordingly configure a particular processor or processors, for example, to constitute a particular hardware module at one instance of time and to constitute a different hardware module at a different instance of time.

[0097] Hardware modules can provide information to, and receive information from, other hardware modules. Accordingly, the described hardware modules may be regarded as being communicatively coupled. Where multiple hardware modules exist contemporaneously, communications may be achieved through signal transmission (e.g., over appropriate circuits and buses) between or among two or more of the hardware modules. In embodiments in which multiple hardware modules are configured or instantiated at different times, communications between such hardware modules may be achieved, for example, through the storage and retrieval of information in memory structures to which the multiple hardware modules have access. For example, one hardware module may perform an operation and store the output of that operation in a memory device to which it is communicatively coupled. A further hardware module may then, at a later time, access the memory device to retrieve and process the stored output. Hardware modules may also initiate communications with input or output devices, and can operate on a resource (e.g., a collection of information).

[0098] The various operations of example methods described herein may be performed, at least partially, by one or more processors that are temporarily configured (e.g., by software) or permanently configured to perform the relevant operations. Whether temporarily or permanently configured, such processors may constitute processor-implemented modules that operate to perform one or more operations or functions described herein. As used herein, "processor-implemented module" refers to a hardware module implemented using one or more processors.

[0099] Similarly, the methods described herein may be at least partially processor-implemented, with a particular processor or processors being an example of hardware. For example, at least some of the operations of a method may be performed by one or more processors or processor-implemented modules. Moreover, the one or more processors may also operate to support performance of the relevant operations in a "cloud computing" environment or as a "software as a service" (SaaS). For example, at least some of the operations may be performed by a group of computers (as examples of machines including processors), with these operations being accessible via a network (e.g., the Internet) and via one or more appropriate interfaces (e.g., an application program interface (API)).

[0100] The performance of certain of the operations may be distributed among the processors, not only residing within a single machine, but deployed across a number of machines. In some example embodiments, the processors or processor-implemented modules may be located in a single geographic location (e.g., within a home environment, an office environment, or a server farm). In other example embodiments, the processors or processor-implemented modules may be distributed across a number of geographic locations.

[0101] FIG. **11** is a block diagram **1100** illustrating an example software architecture **1102**, which may be used in conjunction with various hardware architectures herein described to provide a job scheduler system **1101**, which may be similar to the job scheduler **230** as described above. FIG. **11** is a non-limiting example of a software architecture and it will be appreciated that many other architectures may be implemented to facilitate the functionality described herein. The software architecture **1102** may execute on hardware such as a machine **1200** of FIG. **12** that includes, among other things, processors **1210**, memory **1230**, and input/output (I/O) components **1250**. A representative hardware layer **1104** is illustrated and can represent, for example, the machine **1200** of FIG. **12**. The representative hardware layer **1104** includes a processing unit **1106** having associated executable instructions **1108**. The executable instructions **1108** represent the executable instructions of the software architecture **1102**, including implementation of the methods, modules and so forth described herein. The hardware layer **1104** also includes memory/storage **1110**, which also includes the executable instructions **1108**. The hardware layer **1104** may also comprise other hardware **1112**.

[0102] In the example architecture of FIG. **11**, the software architecture **1102** may be conceptualized as a stack of layers where each layer provides particular functionality. For example, the software architecture **1102** may include layers such as an operating system **1114**, libraries **1116**, frameworks or middleware **1118**, applications **1120** and a presentation layer **1144**. Operationally, the applications **1120** and/or other components within the layers may invoke API calls **1124** through the software stack and receive a response as messages **1126**. The layers illustrated are representative in nature and not all software architectures have all layers. For example, some mobile or special purpose operating systems may not provide the frameworks/middleware **1118**, while others may provide such a layer. Other software architectures may include additional or different layers.

[0103] The operating system **1114** may manage hardware resources and provide common services. The operating system **1114** may include, for example, a kernel **1128**, services **1130**, and drivers **1132**. The kernel **1128** may act as an abstraction layer between the hardware and the other software layers. For example, the kernel **1128** may be responsible for memory management, processor management (e.g., scheduling), component management, networking, security settings, and so on. The services **1130** may provide other common services for the other software layers. The drivers **1132** may be responsible for controlling or interfacing with the underlying hardware. For instance, the drivers **1132** may include display drivers, camera drivers, Bluetooth® drivers, flash memory drivers, serial communication drivers (e.g., Universal Serial Bus (USB) drivers), Wi-Fi® drivers, audio drivers, power management drivers, and so forth depending on the hardware configuration.

[0104] The libraries **1116** may provide a common infrastructure that may be used by the applications **1120** and/or other components and/or layers. The libraries **1116** typically provide functionality that allows other software modules to perform tasks in an easier fashion than to interface directly with the underlying operating system **1114** functionality (e.g., kernel **1128**, services **1130** and/or drivers **1132**). The libraries **1116** may include system libraries **1134** (e.g., C standard library) that may provide functions such as memory allocation functions, string manipulation functions, math-

ematic functions, and the like. In addition, the libraries **1116** may include API libraries **1136** such as media libraries (e.g., libraries to support presentation and manipulation of various media format such as MPEG4, H.264, MP3, AAC, AMR, JPG, PNG), graphics libraries (e.g., an OpenGL framework that may be used to render 2D and 3D graphic content on a display), database libraries (e.g., SQLite that may provide various relational database functions), web libraries (e.g., WebKit that may provide web browsing functionality), and the like. The libraries **1116** may also include a wide variety of other libraries **1138** to provide many other APIs to the applications **1120** and other software components/modules.

[0105] The frameworks **1118** (also sometimes referred to as middleware) provide a higher-level common infrastructure that may be used by the applications **1120** and/or other software components/modules. For example, the frameworks/middleware **1118** may provide various graphic user interface (GUI) functions, high-level resource management, high-level location services, and so forth. The frameworks/middleware **1118** may provide a broad spectrum of other APIs that may be utilized by the applications **1120** and/or other software components/modules, some of which may be specific to a particular operating system or platform.

[0106] The applications **1120** include built-in applications **1140** and/or third-party applications **1142**. Examples of representative built-in applications **1140** may include, but are not limited to, a contacts application, a browser application, a book reader application, a location application, a media application, a messaging application, and/or a game application. Third-party applications **1142** may include any an application developed using the Android™ or iOS™ software development kit (SDK) by an entity other than the vendor of the particular platform, and may be mobile software running on a mobile operating system such as iOS™, Android™, Windows® Phone, or other mobile operating systems. The third-party applications **1142** may invoke the API calls **1124** provided by the mobile operating system such as operating system **1114** to facilitate functionality described herein.

[0107] The applications **1120** may use built-in operating system functions (e.g., kernel **1128**, services **1130** and/or drivers **1132**), libraries **1116**, or frameworks/middleware **1118** to create user interfaces to interact with users of the system. Alternatively, or additionally, in some systems, interactions with a user may occur through a presentation layer, such as the presentation layer **1144**. In these systems, the application/module "logic" can be separated from the aspects of the application/module that interact with a user.

[0108] Some software architectures use virtual machines. In the example of FIG. **11**, this is illustrated by a virtual machine **1148**. The virtual machine **1148** creates a software environment where applications/modules can execute as if they were executing on a hardware machine (such as the machine **1200** of FIG. **12**, for example). The virtual machine **1148** is hosted by a host operating system (e.g., operating system **1114**) and typically, although not always, has a virtual machine monitor **1146**, which manages the operation of the virtual machine **1148** as well as the interface with the host operating system (i.e., operating system **1114**). A software architecture executes within the virtual machine **1148** such as an operating system **1150**, libraries **1152**, frameworks **1154**, applications **1156**, and/or a presentation layer **1158**. These layers of software architecture executing within the virtual machine **1148** can be the same as corresponding layers previously described or may be different.

[0109] FIG. **12** is a block diagram illustrating components of a machine **1200**, according to some example embodiments, configured to read instructions from a machine-readable medium (e.g., a machine-readable storage medium) and perform any one or more of the methodologies discussed herein. In some embodiments, the machine **110** is similar to the computing device **200** shown in FIGS. **2-10**. Specifically, FIG. **12** shows a diagrammatic representation of the machine **1200** in the example form of a computer system, within which instructions **1216** (e.g., software, a program, an application, an applet, an app, or other executable code) for causing the machine **1200** to perform any one or more of the methodologies discussed herein may be executed. As such, the instructions **1216** may be used to implement modules or components described herein. The instructions transform the general, non-programmed machine into a particular machine programmed to carry out the described and illustrated functions in the manner described. In alternative embodiments, the machine **1200** operates as a standalone device or may be coupled (e.g., networked) to other machines. In a networked deployment, the machine **1200** may operate in the capacity of a server machine or a client machine in a server-client network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine **1200** may comprise, but not be limited to, a server computer, a client computer, a personal computer (PC), a tablet computer, a laptop computer, a netbook, a set-top box (STB), a personal digital assistant (PDA), an entertainment media system, a cellular telephone, a smart phone, a mobile device, a wearable device (e.g., a smart watch), a smart home device (e.g., a smart appliance), other smart devices, a web appliance, a network router, a network switch, a network bridge, or any machine capable of executing the instructions **1216**, sequentially or otherwise, that specify actions to be taken by the machine **1200**. Further, while only a single machine **1200** is illustrated, the term "machine" shall also be taken to include a collection of machines that individually or jointly execute the instructions **1216** to perform any one or more of the methodologies discussed herein.

[0110] The machine **1200** may include processors **1210**, memory **1230**, and input/output (I/O) components **1250**, which may be configured to communicate with each other such as via a bus **1202**. In an example embodiment, the processors **1210** (e.g., a Central Processing Unit (CPU), a Reduced Instruction Set Computing (RISC) processor, a Complex Instruction Set Computing (CISC) processor, a Graphics Processing Unit (GPU), a Digital Signal Processor (DSP), an ASIC, a Radio-Frequency Integrated Circuit (RFIC), another processor, or any suitable combination thereof) may include, for example, a processor **1212** and a processor **1214** that may execute the instructions **1216**. The term "processor" is intended to include multi-core processor that may comprise two or more independent processors (sometimes referred to as "cores") that may execute instructions contemporaneously. Although FIG. **12** shows multiple processors, the machine **1200** may include a single processor with a single core, a single processor with multiple cores (e.g., a multi-core processor), multiple processors with a single core, multiple processors with multiples cores, or any combination thereof.

[0111] The memory/storage **1230** may include a memory, such as a main memory **1232**, a static memory **1234**, or other memory, and a storage unit **1236**, all accessible to the processors **1210** such as via the bus **1202**. The storage unit **1236** and memory **1232**, **1234** store the instructions **1216** embodying any one or more of the methodologies or functions described herein. The instructions **1216** may also reside, completely or partially, within the memory **1232**, **1234**, within the storage unit **1236**, within at least one of the processors **1210** (e.g., within the processor's cache memory), or any suitable combination thereof, during execution thereof by the machine **1200**. Accordingly, the memory **1232**, **1234**, the storage unit **1236**, and the memory of processors **1210** are examples of machine-readable media **1238**.

[0112] As used herein, "machine-readable medium" means a device able to store instructions and data temporarily or permanently and may include, but is not limited to, random-access memory (RAM), read-only memory (ROM), buffer memory, flash memory, optical media, magnetic media, cache memory, other types of storage (e.g., Erasable Programmable Read-Only Memory (EEPROM)) and/or any suitable combination thereof. The term "machine-readable medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, or associated caches and servers) able to store the instructions **1216**. The term "machine-readable medium" shall also be taken to include any medium, or combination of multiple media, that is capable of storing instructions (e.g., instructions **1216**) for execution by a machine (e.g., machine **1200**), such that the instructions, when executed by one or more processors of the machine **1200** (e.g., processors **1210**), cause the machine **1200** to perform any one or more of the methodologies described herein. Accordingly, a "machine-readable medium" refers to a single storage apparatus or device, as well as "cloud-based" storage systems or storage networks that include multiple storage apparatus or devices. The term "machine-readable medium" excludes signals per se.

[0113] The I/O components **1250** may include a wide variety of components to receive input, provide output, produce output, transmit information, exchange information, capture measurements, and so on. The specific I/O components **1250** that are included in a particular machine will depend on the type of machine. For example, portable machines such as mobile phones will likely include a touch input device or other such input mechanisms, while a headless server machine will likely not include such a touch input device. It will be appreciated that the I/O components **1250** may include many other components that are not shown in FIG. **12**. The I/O components **1250** are grouped according to functionality merely for simplifying the following discussion and the grouping is in no way limiting. In various example embodiments, the I/O components **1250** may include output components **1252** and input components **1254**. The output components **1252** may include visual components (e.g., a display such as a plasma display panel (PDP), a light emitting diode (LED) display, a liquid crystal display (LCD), a projector, or a cathode ray tube (CRT)), acoustic components (e.g., speakers), haptic components (e.g., a vibratory motor, resistance mechanisms), other signal generators, and so forth. The input components **1254** may include alphanumeric input components (e.g., a keyboard, a touch screen configured to receive alphanumeric input, a photo-optical keyboard, or other alphanumeric input components), point based input components (e.g., a mouse, a touchpad, a trackball, a joystick, a motion sensor, or another pointing instrument), tactile input components (e.g., a physical button, a touch screen that provides location and/or force of touches or touch gestures, or other tactile input components), audio input components (e.g., a microphone), and the like.

[0114] In further example embodiments, the I/O components **1250** may include biometric components **1256**, motion components **1258**, environmental components **1260**, or position components **1262**, among a wide array of other components. For example, the biometric components **1256** may include components to detect expressions (e.g., hand expressions, facial expressions, vocal expressions, body gestures, or eye tracking), measure biosignals (e.g., blood pressure, heart rate, body temperature, perspiration, or brain waves), identify a person (e.g., voice identification, retinal identification, facial identification, fingerprint identification, or electroencephalogram based identification), and the like. The motion components **1258** may include acceleration sensor components (e.g., accelerometer), gravitation sensor components, rotation sensor components (e.g., gyroscope), and so forth. The environmental components **1260** may include, for example, illumination sensor components (e.g., photometer), temperature sensor components (e.g., one or more thermometers that detect ambient temperature), humidity sensor components, pressure sensor components (e.g., barometer), acoustic sensor components (e.g., one or more microphones that detect background noise), proximity sensor components (e.g., infrared sensors that detect nearby objects), gas sensors (e.g., gas detection sensors to detection concentrations of hazardous gases for safety or to measure pollutants in the atmosphere), or other components that may provide indications, measurements, or signals corresponding to a surrounding physical environment. The position components **1262** may include location sensor components (e.g., a Global Position System (GPS) receiver component), altitude sensor components (e.g., altimeters or barometers that detect air pressure from which altitude may be derived), orientation sensor components (e.g., magnetometers), and the like.

[0115] Communication may be implemented using a wide variety of technologies. The I/O components **1250** may include communication components **1264** operable to couple the machine **1200** to a network **1280** or devices **1270** via a coupling **1282** and a coupling **1272** respectively. For example, the communication components **1264** may include a network interface component or other suitable device to interface with the network **1280**. In further examples, the communication components **1264** may include wired communication components, wireless communication components, cellular communication components, Near Field Communication (NFC) components, Bluetooth® components (e.g., Bluetooth® Low Energy), Wi-Fi® components, and other communication components to provide communication via other modalities. The devices **1270** may be another machine or any of a wide variety of peripheral devices (e.g., a peripheral device coupled via a USB).

[0116] Moreover, the communication components **1264** may detect identifiers or include components operable to detect identifiers. For example, the communication components **1264** may include Radio Frequency Identification (RFID) tag reader components, NFC smart tag detection

components, optical reader components (e.g., an optical sensor to detect one-dimensional bar codes such as Universal Product Code (UPC) bar code, multi-dimensional bar codes such as Quick Response (QR) code, Aztec code, Data Matrix, Dataglyph, MaxiCode, PDF417, Ultra Code, UCC RSS-2D bar code, and other optical codes), or acoustic detection components (e.g., microphones to identify tagged audio signals). In addition, a variety of information may be derived via the communication components **1262**, such as, location via Internet Protocol (IP) geo-location, location via Wi-Fi® signal triangulation, location via detecting a NFC beacon signal that may indicate a particular location, and so forth.

[0117] Throughout this specification, plural instances may implement components, operations, or structures described as a single instance. Although individual operations of one or more methods are illustrated and described as separate operations, one or more of the individual operations may be performed concurrently, and nothing requires that the operations be performed in the order illustrated. Structures and functionality presented as separate components in example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be implemented as separate components. These and other variations, modifications, additions, and improvements fall within the scope of the subject matter herein.

[0118] The embodiments illustrated herein are described in sufficient detail to enable those skilled in the art to practice the teachings disclosed. Other embodiments may be used and derived therefrom, such that structural and logical substitutions and changes may be made without departing from the scope of this disclosure. The Detailed Description, therefore, is not to be taken in a limiting sense, and the scope of various embodiments is defined only by the appended claims, along with the full range of equivalents to which such claims are entitled.

[0119] As used herein, the term "or" may be construed in either an inclusive or exclusive sense. Moreover, plural instances may be provided for resources, operations, or structures described herein as a single instance. Additionally, boundaries between various resources, operations, modules, engines, and data stores are somewhat arbitrary, and particular operations are illustrated in a context of specific illustrative configurations. Other allocations of functionality are envisioned and may fall within a scope of various embodiments of the present disclosure. In general, structures and functionality presented as separate resources in the example configurations may be implemented as a combined structure or resource. Similarly, structures and functionality presented as a single resource may be implemented as separate resources. These and other variations, modifications, additions, and improvements fall within the scope of embodiments of the present disclosure as represented by the appended claims. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. A job scheduler system comprising:

one or more hardware processors;

a memory including a job group queue stored in the memory, the job group queue configured to store a plurality of job groups in the memory, each job group of the plurality of job groups identifies one or more jobs for execution by the one or more hardware processors;

a job scheduler engine, executable by the one or more hardware processors, configured to perform operations comprising:

creating a first job group in the job group queue, the first job group includes a generation counter having an initial value;

receiving a first request to steal the first job group;

determining a state of the first job group based at least in part on the generation counter, the state indicating that the first job group is available to steal;

based on the determining the state of the first job group, atomically incrementing the generation counter, thereby making the first job group unavailable for stealing; and

altering an execution order of the first job group ahead of at least one other job group in the job group queue.

2. The job scheduler system of claim **1**, wherein the first job group includes a first job list identifying a first plurality of jobs, wherein said altering further includes sending the first plurality of jobs to an execution stack.

3. The job scheduler system of claim **2**, wherein sending the first plurality of jobs to the execution stack further includes removing the first plurality of jobs from the first job group, thereby making the first job list empty, wherein the job scheduler engine is further configured to perform operations comprising:

receiving a second request to steal the first job group approximately contemporaneously with the first request;

based on receiving the second request, determining a state of the first job group based at least in part on the generation counter, the state indicating that the first job group is available to steal; and

failing to steal the first job group for the second request based on the first job list being empty.

4. The job scheduler system of claim **1**, wherein the first job group is dependent upon a second job group, wherein the first job group includes a first job list and the second job group includes a second job list, wherein the job scheduler engine is further configured to perform operations comprising:

determining that the first job group is dependent upon the second job group; and

based on the determining that the first job group is dependent upon the second job group:

adding the first job list to the end of the second job list; and

initiating a steal operation for the second job group.

5. The job scheduler system of claim **1**, wherein the memory further includes an execution stack stored in the memory, wherein the first job group occupies a first region in the memory, wherein the first job group includes a first job list, wherein the job scheduler engine is further configured to perform operations comprising:

sending the first job list to the execution stack;

deleting the contents of the first job group; and

reusing the first job group for another job group without deallocating the first region in the memory.

6. The job scheduler system of claim **1**, wherein the job scheduler engine is further configured to perform operations comprising:

determining that the first job group has been executed; and

based on the determining that the first job group has been executed, atomically incrementing the generation counter.

7. The job scheduler system of claim **1**, wherein processing the first request to steal the first job group does not use a waiting lock on the job group queue.

8. A computer-implemented method comprising:

creating a first job group in a job group queue, the job group queue is stored in a memory, the job group queue is configured to store a plurality of job groups in the memory, each job group of the plurality of job groups identifies one or more jobs for execution by the one or more hardware processors, the first job group includes a generation counter having an initial value;

receiving a first request to steal the first job group;

determining a state of the first job group based at least in part on the generation counter, the state indicating that the first job group is available to steal;

based on the determining the state of the first job group, atomically incrementing the generation counter, thereby making the first job group unavailable for stealing; and

altering an execution order of the first job group ahead of at least one other job group in the job group queue.

9. The method of claim **8**, wherein the first job group includes a first job list, wherein altering further includes sending the first job list to an execution stack.

10. The method of claim **9**, wherein sending the first plurality of jobs to the execution stack further includes removing the first plurality of jobs from the first job group, thereby making the first job list empty, the method further comprising:

receiving a second request to steal the first job group approximately contemporaneously with the first request;

based on receiving the second request, determining a state of the first job group based at least in part on the generation counter, the state indicating that the first job group is available to steal; and

failing to steal the first job group for the second request based on the first job list being empty.

11. The method of claim **8**, wherein the first job group is dependent upon a second job group, wherein the first job group includes a first job list and the second job group includes a second job list, the method further comprising:

determining that the first job group is dependent upon the second job group; and

based on the determining that the first job group is dependent upon the second job group:

adding the first job list to the end of the second job list; and

initiating a steal operation for the second job group.

12. The method of claim **8**, wherein the memory further includes an execution stack stored in the memory, wherein the first job group occupies a first region in the memory, wherein the first job group includes a first job list, the method further comprising:

sending the first job list to an execution stack;

deleting the contents of the first job group; and

reusing the first job group for another job group without deallocating the first region in the memory.

13. The method of claim **8**, further comprising:

determining that the first job group has been executed; and

based on the determining that the first job group has been executed, atomically incrementing the generation counter.

14. The method of claim **8**, wherein processing the first request to steal the first job group does not use a waiting lock on the job group queue.

15. A non-transitory machine-readable medium storing processor-executable instructions which, when executed by a processor, cause the processor to perform operations comprising:

creating a first job group in a job group queue, the job group queue is stored in a memory, the job group queue is configured to store a plurality of job groups in the memory, each job group of the plurality of job groups identifies one or more jobs for execution by the one or more hardware processors, the first job group includes a generation counter having an initial value;

receiving a first request to steal the first job group;

determining a state of the first job group based at least in part on the generation counter, the state indicating that the first job group is available to steal;

based on the determining the state of the first job group, atomically incrementing the generation counter, thereby making the first job group unavailable for stealing; and

altering an execution order of the first job group ahead of at least one other job group in the job group queue.

16. The machine-readable medium of claim **15**, wherein the first job group includes a first job list, wherein altering further includes sending the first job list to an execution stack.

17. The machine-readable medium of claim **15**, wherein the first job group is dependent upon a second job group, wherein the first job group includes a first job list and the second job group includes a second job list, wherein the processor-executable instructions further cause the processor to perform operations comprising:

determining that the first job group is dependent upon the second job group; and

based on the determining that the first job group is dependent upon the second job group:

adding the first job list to the end of the second job list; and

initiating a steal operation for the second job group.

18. The machine-readable medium of claim **15**, wherein the memory further includes an execution stack stored in the memory, wherein the first job group occupies a first region in the memory, wherein the first job group includes a first job list, wherein the processor-executable instructions further cause the processor to perform operations comprising:

sending the first job list to an execution stack;

deleting the contents of the first job group; and

reusing the first job group for another job group without deallocating the first region in the memory.

19. The machine-readable medium of claim **15**, wherein the processor-executable instructions further cause the processor to perform operations comprising:

determining that the first job group has been executed; and

based on the determining that the first job group has been executed, atomically incrementing the generation counter.

20. The machine-readable medium of claim **15**, wherein processing the first request to steal the first job group does not use a waiting lock on the job group queue.

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