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SYSTEMS AND METHODS OF INSTRUCTION SETS FOR CACHE PROCESSORS

Abstract

Provided are systems, methods, and apparatuses of instruction sets for cache processor (e.g., of tiered memory devices). In one or more examples, the systems, devices, and methods include receiving, from a memory controller, a memory request based on a first cache processor of a cache executing a poll command of an instruction set that is configured to program at least one aspect of the cache in association with at least one of a cache control and status register (CSR) or a device CSR; determining that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with a second cache processor of the cache; and processing, via the first cache processor, the memory request based on determining that the data associated with the memory request is stored in the cache.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Ser. No. 63/551,488, filed Feb. 8, 2024, which is incorporated by reference herein for all purposes.

TECHNICAL FIELD

[0002] The disclosure relates generally to memory systems. In particular, the subject matter relates to systems and methods of instruction sets for cache processor (e.g., of tiered memory devices).

BACKGROUND

[0003] The present background section is intended to provide context only, and the disclosure of any concept in this section does not constitute an admission that said concept is prior art.

[0004] Memory management includes a form of resource management applied to computer memory. Some aspects of memory management include providing dynamic allocation of portions of memory to programs at the programs' request, and free the allocations for reuse when the portions of memory are no longer needed. Improvements in memory management are needed with regards to high-performance computing and artificial intelligence (AI) systems.

SUMMARY

[0005] In various embodiments, the systems and methods described herein include systems, methods, and apparatuses of instruction sets for cache processor (e.g., of tiered memory devices). In some aspects, the techniques described herein relate to a method of programmable cache algorithms, the method including: receiving, from a memory controller, a memory request based on a first cache processor of a cache executing a poll command of an instruction set that is configured to program at least one aspect of the cache in association with at least one of a cache control and status register (CSR) or a device CSR; determining that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with a second cache processor of the cache; and processing, via the first cache processor, the memory request based on determining that the data associated with the memory request is stored in the cache.

[0006] In some aspects, the techniques described herein relate to a method, wherein processing the memory request includes the first cache processor reading the data associated with the memory request from the cache based on the memory request including a read request.

[0007] In some aspects, the techniques described herein relate to a method, wherein processing the memory request includes the first cache processor modifying the data that is in the cache and associated with the memory request based on the memory request including a write request.

[0008] In some aspects, the techniques described herein relate to a method, wherein processing the memory request includes the first cache processor executing a tag load command of the instruction set to load a tag of data in the cache to a tag register, executing a tag compare command of the instruction set to compare the tag of the data in the cache to a tag of the data associated with the memory request, updating an access frequency attribute of the tag of the data in the cache, and executing a tag store command of the instruction set to store, in the metadata of the shared memory, the updated tag of the data in the cache.

[0009] In some aspects, the techniques described herein relate to a method, further including determining a memory address of the data associated with the memory request based on the first cache processor querying the cache CSR.

[0010] In some aspects, the techniques described herein relate to a method, wherein the first cache

processor querying the metadata is based on the first cache processor querying the device CSR for an address of the metadata.

[0011] In some aspects, the techniques described herein relate to a method, wherein the first cache processor executing the poll command of the instruction set is based on the first cache processor querying the device CSR for a starting address of a cache request routine.

[0012] In some aspects, the techniques described herein relate to a method, further including accessing, via the first cache processor, a storage device to process the second memory request, the storage device being accessed based on the first cache processor determining a state of data associated with a second memory request in relation to the cache and the storage device.

[0013] In some aspects, the techniques described herein relate to a method, wherein processing the memory request includes the first cache processor writing data to the storage device based on the second memory request including a second write request or reading data from the storage device based on the second memory request including a second read request.

[0014] In some aspects, the techniques described herein relate to a method, wherein processing the second memory request includes the first cache processor executing a tag load command of the instruction set to load a tag of data in the cache to a tag register, executing a tag compare command of the instruction set to compare the tag of data in the cache to a tag of the data associated with the second memory request.

[0015] In some aspects, the techniques described herein relate to a method, wherein processing the second memory request includes the second cache processor: determining that the cache includes available space to store the data associated with the second memory request based on the second cache processor querying the cache CSR for a status of the cache; copying the data associated with the second memory request from a storage device to the cache based on the second memory request including a read request or writing the data associated with the second memory request to the cache based on the second memory request including a write request; and executing a tag store command of the instruction set to store, in the metadata of the shared memory, a tag of the data associated with the second memory request.

[0016] In some aspects, the techniques described herein relate to a method, wherein processing the second memory request includes the second cache processor: determining that the cache is full based on the second cache processor querying the cache CSR for a status of the cache; evicting a portion of data from the cache based on the second cache processor implementing an eviction policy that the second cache processor indicates in at least one command of the instruction set; and writing the portion of data evicted from the cache to a storage device based on the second cache processor determining a mismatch between the portion of data evicted from the cache and data in the storage device associated with the portion of data evicted from the cache.

[0017] In some aspects, the techniques described herein relate to a method, wherein: the instruction set is implemented on a cache-coherent tiered memory device that includes the memory controller, the cache, the first cache processor, the second cache processor, and a storage device, the cache includes a dynamic random-access memory, and the storage device includes a NAND storage device.

[0018] In some aspects, the techniques described herein relate to a cache device, including: a cache; a storage device; a memory controller; a first cache processor; and a second cache processor, wherein: the memory controller is configured to receive a memory request based on the first cache processor executing a poll command of an instruction set that is configured to program at least one aspect of the cache in association with at least one of a cache control and status register (CSR) or a device CSR; the first cache processor is configured to determine that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with the second cache processor; and the first cache processor is configured to process the memory request based on determining that the data associated with the memory request is stored in the cache.

[0019] In some aspects, the techniques described herein relate to a cache device, wherein the first cache processor processing the memory request includes the first cache processor reading the data associated with the memory request from the cache based on the memory request including a read request.

[0020] In some aspects, the techniques described herein relate to a cache device, wherein the first cache processor processing the memory request includes the first cache processor modifying the data that is in the cache and associated with the memory request based on the memory request including a write request.

[0021] In some aspects, the techniques described herein relate to a cache device, wherein the first cache processor processing the memory request includes the first cache processor executing a tag load command of the instruction set to load a tag of data in the cache to a tag register, executing a tag compare command of the instruction set to compare the tag of the data in the cache to a tag of the data associated with the memory request, updating an access frequency attribute of the tag of the data in the cache, and executing a tag store command of the instruction set to store, in the metadata of the shared memory, the updated tag of the data in the cache.

[0022] In some aspects, the techniques described herein relate to a cache device, further including the first cache processor being configured to determine a memory address of the data associated with the memory request based on the first cache processor querying the cache CSR.

[0023] In some aspects, the techniques described herein relate to a non-transitory computer-readable medium storing code that includes instructions executable by a first cache processor to: receive, from a memory controller, a memory request based on the first cache processor executing a poll command of an instruction set that is configured to program at least one aspect of a cache in association with at least one of a cache control and status register (CSR) or a device CSR; [0024] determine that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with a second cache processor of the cache; and process the memory request based on determining that the data associated with the memory request is stored in the cache.

[0025] In some aspects, the techniques described herein relate to a non-transitory computer-readable medium, wherein the first cache processor processing the memory request includes the first cache processor reading the data associated with the memory request from the cache based on the memory request including a read request.

[0026] A computer-readable medium is disclosed. The computer-readable medium can store instructions that, when executed by a computer, cause the computer to perform substantially the same or similar operations as described herein are further disclosed. Similarly, non-transitory computer-readable media, devices, and systems for performing substantially the same or similar operations as described herein are further disclosed.

[0027] The systems and methods described herein include multiple advantages and benefits. For example, the systems and methods of instruction sets for cache processor (e.g., of tiered memory devices) described herein have a relatively high throughput and increase memory bandwidth of a given system. The systems and methods described herein enable a user to program cache algorithms based on cache processor instruction sets. The cache algorithms (e.g., custom cache algorithms) can be downloaded to device memory (e.g., device command memory). The systems and methods described herein provide cache instruction sets that enable a user to adapt cache algorithms to a given workload of an application. Based on the systems and methods of programmable cache processors described herein, devices (e.g., CXL tiered memory devices and systems) can be enhanced to support broad applications with improved performance. The systems and methods described herein reduce latency associated with memory operations of tiered memory devices. Additionally, the systems and methods of instruction sets for cache processor (e.g., of tiered memory devices) described herein have a relatively low implementation cost.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] The above-mentioned aspects and other aspects of the present systems and methods will be better understood when the present application is read in view of the following figures in which like numbers indicate similar or identical elements. Further, the drawings provided herein are for purpose of illustrating certain embodiments only; other embodiments, which may not be explicitly illustrated, are not excluded from the scope of this disclosure.

[0029] These and other features and advantages of the present disclosure will be appreciated and understood with reference to the specification, claims, and appended drawings, wherein:

[0030] FIG. 1 illustrates an example system in accordance with one or more implementations as described herein.

[0031] FIG. 2 illustrates details of the system of FIG. 1, according to one or more implementations as described herein.

[0032] FIG. 3 illustrates an example system in accordance with one or more implementations as described herein.

[0033] FIG. 4 illustrates an example data structure in accordance with one or more implementations as described herein.

[0034] FIG. 5 illustrates an example data structure in accordance with one or more implementations as described herein.

[0035] FIG. 6 illustrates an example data structure in accordance with one or more implementations as described herein.

[0036] FIGS. 7-14 illustrate example commands in accordance with one or more implementations as described herein.

[0037] FIG. 15 depicts a flow diagram illustrating an example method associated with the disclosed systems, in accordance with example implementations described herein.

[0038] FIG. 16 depicts a flow diagram illustrating an example method associated with the disclosed systems, in accordance with example implementations described herein.

[0039] While the present systems and methods are susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the present systems and methods to the particular form disclosed, but to the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present systems and methods as defined by the appended claims.

DETAILED DESCRIPTION OF VARIOUS EMBODIMENTS

[0040] The details of one or more embodiments of the subject matter described herein are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

[0041] Various embodiments of the present disclosure now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments are shown. Indeed, the disclosure may be embodied in many forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. The term “or” is used herein in both the alternative and conjunctive sense, unless otherwise indicated. The terms “illustrative” and “example” are used to be examples with no indication of quality level. Like numbers refer to like elements throughout. Arrows in each of the figures depict bi-directional data flow and/or bi-directional data flow capabilities. The terms “path,” “pathway” and “route” are used interchangeably herein.

[0042] Embodiments of the present disclosure may be implemented in various ways, including as

computer program products that comprise articles of manufacture. A computer program product may include a non-transitory computer-readable storage medium storing applications, programs, program components, scripts, source code, program code, object code, byte code, compiled code, interpreted code, machine code, executable instructions, and/or the like (also referred to herein as executable instructions, instructions for execution, computer program products, program code, and/or similar terms used herein interchangeably). Such non-transitory computer-readable storage media include all computer-readable media (including volatile and non-volatile media).

[0043] In one embodiment, a non-volatile computer-readable storage medium may include a floppy disk, flexible disk, hard disk, solid-state storage (SSS) (for example a solid-state drive (SSD)), solid state card (SSC), solid state module (SSM), enterprise flash drive, magnetic tape, or any other non-transitory magnetic medium, and/or the like. A non-volatile computer-readable storage medium may include a punch card, paper tape, optical mark sheet (or any other physical medium with patterns of holes or other optically recognizable indicia), compact disc read only memory (CD-ROM), compact disc-rewritable (CD-RW), digital versatile disc (DVD), Blu-ray disc (BD), any other non-transitory optical medium, and/or the like. Such a non-volatile computer-readable storage medium may include read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash memory (for example Serial, NAND, NOR, and/or the like), multimedia memory cards (MMC), secure digital (SD) memory cards, SmartMedia cards, CompactFlash (CF) cards, Memory Sticks, and/or the like. Further, a non-volatile computer-readable storage medium may include conductive-bridging random access memory (CBRAM), phase-change random access memory (PRAM), ferroelectric random-access memory (FeRAM), non-volatile random-access memory (NVRAM), magnetoresistive random-access memory (MRAM), resistive random-access memory (RRAM), Silicon-Oxide-Nitride-Oxide-Silicon memory (SONOS), floating junction gate random access memory (FJG RAM), Millipede memory, racetrack memory, and/or the like.

[0044] In one embodiment, a volatile computer-readable storage medium may include random access memory (RAM), dynamic random access memory (DRAM), static random access memory (SRAM), fast page mode dynamic random access memory (FPM DRAM), extended data-out dynamic random access memory (EDO DRAM), synchronous dynamic random access memory (SDRAM), double data rate synchronous dynamic random access memory (DDR SDRAM), double data rate type two synchronous dynamic random access memory (DDR2 SDRAM), double data rate type three synchronous dynamic random access memory (DDR3 SDRAM), Rambus dynamic random access memory (RDRAM), Twin Transistor RAM (TTRAM), Thyristor RAM (T-RAM), Zero-capacitor (Z-RAM), Rambus in-line memory component (RIMM), dual in-line memory component (DIMM), single in-line memory component (SIMM), video random access memory (VRAM), cache memory (including various levels), flash memory, register memory, and/or the like. It will be appreciated that where embodiments are described to use a computer-readable storage medium, other types of computer-readable storage media may be substituted for or used in addition to the computer-readable storage media described above.

[0045] As should be appreciated, various embodiments of the present disclosure may be implemented as methods, apparatus, systems, computing devices, computing entities, and/or the like. As such, embodiments of the present disclosure may take the form of an apparatus, system, computing device, computing entity, and/or the like executing instructions stored on a computer-readable storage medium to perform certain steps or operations. Thus, embodiments of the present disclosure may take the form of a hardware embodiment, a computer program product embodiment, and/or an embodiment that comprises a combination of computer program products and hardware performing certain steps or operations.

[0046] Embodiments of the present disclosure are described below with reference to block diagrams and flowchart illustrations. Thus, it should be understood that each block of the block

diagrams and flowchart illustrations may be implemented in the form of a computer program product, a hardware embodiment, a combination of hardware and computer program products, and/or apparatus, systems, computing devices, computing entities, and/or the like carrying out instructions, operations, steps, and similar words used interchangeably (for example the executable instructions, instructions for execution, program code, and/or the like) on a computer-readable storage medium for execution. For example, retrieval, loading, and execution of code may be performed sequentially, such that one instruction is retrieved, loaded, and executed at a time. In some example embodiments, retrieval, loading, and/or execution may be performed in parallel, such that multiple instructions are retrieved, loaded, and/or executed together. Thus, such embodiments can produce specifically configured machines performing the steps or operations specified in the block diagrams and flowchart illustrations. Accordingly, the block diagrams and flowchart illustrations support various combinations of embodiments for performing the specified instructions, operations, or steps.

[0047] Reference throughout this specification to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment may be included in at least one embodiment disclosed herein. Thus, the appearances of the phrases “in one embodiment” or “in an embodiment” or “according to one embodiment” (or other phrases having similar import) in various places throughout this specification may not be necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments. In this regard, as used herein, the word “exemplary” means “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not to be construed as necessarily preferred or advantageous over other embodiments. Additionally, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. Also, depending on the context of discussion herein, a singular term may include the corresponding plural forms and a plural term may include the corresponding singular form. Similarly, a hyphenated term (e.g., “two-dimensional,” “pre-determined,” “pixel-specific,” etc.) may be occasionally interchangeably used with a corresponding non-hyphenated version (e.g., “two dimensional,” “predetermined,” “pixel specific,” etc.), and a capitalized entry (e.g., “Counter Clock,” “Row Select,” “PIXOUT,” etc.) may be interchangeably used with a corresponding non-capitalized version (e.g., “counter clock,” “row select,” “pixout,” etc.). Such occasional interchangeable uses shall not be considered inconsistent with each other.

[0048] Also, depending on the context of discussion herein, a singular term may include the corresponding plural forms and a plural term may include the corresponding singular form. It is further noted that various figures (including component diagrams) shown and discussed herein are for illustrative purpose only, and are not drawn to scale. Similarly, various waveforms and timing diagrams are shown for illustrative purpose only. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity. Further, if considered appropriate, reference numerals have been repeated among the figures to indicate corresponding and/or analogous elements.

[0049] The terminology used herein is for the purpose of describing some example embodiments only and is not intended to be limiting of the claimed subject matter. As used herein, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0050] It will be understood that when an element or layer is referred to as being on, “connected to” or “coupled to” another element or layer, it can be directly on, connected or coupled to the other element or layer or intervening elements or layers may be present. In contrast, when an element is

referred to as being “directly on,” “directly connected to” or “directly coupled to” another element or layer, there are no intervening elements or layers present. Like numerals refer to like elements throughout. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0051] The terms “first,” “second,” etc., as used herein, are used as labels for nouns that they precede, and do not imply any type of ordering (e.g., spatial, temporal, logical, etc.) unless explicitly defined as such. Furthermore, the same reference numerals may be used across two or more figures to refer to parts, components, blocks, circuits, units, or modules having the same or similar functionality. Such usage is, however, for simplicity of illustration and ease of discussion only; it does not imply that the construction or architectural details of such components or units are the same across all embodiments or such commonly-referenced parts/modules are the only way to implement some of the example embodiments disclosed herein.

[0052] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this subject matter belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0053] As used herein, the term “module” refers to any combination of software, firmware and/or hardware configured to provide the functionality described herein in connection with a module. For example, software may be embodied as a software package, code and/or instruction set or instructions, and the term “hardware,” as used in any implementation described herein, may include, for example, singly or in any combination, an assembly, hardwired circuitry, programmable circuitry, state machine circuitry, and/or firmware that stores instructions executed by programmable circuitry. The modules may, collectively or individually, be embodied as circuitry that forms part of a larger system, for example, but not limited to, an integrated circuit (IC), system on chip (SoC), an assembly, and so forth.

[0054] The provided description is presented to enable one of ordinary skill in the art to make and use the subject matter disclosed herein and to incorporate it in the context of particular applications. While the following is directed to specific examples, other and further examples may be devised without departing from the basic scope thereof.

[0055] Various modifications, as well as a variety of uses in different applications, will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to a wide range of embodiments. Thus, the subject matter disclosed herein is not intended to be limited to the embodiments presented, but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[0056] In the description provided, numerous specific details are set forth in order to provide a more thorough understanding of the subject matter disclosed herein. It will, however, be apparent to one skilled in the art that the subject matter disclosed herein may be practiced without necessarily being limited to these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the subject matter disclosed herein.

[0057] All the features disclosed in this specification (e.g., any accompanying claims, abstract, and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

[0058] Various features are described herein with reference to the figures. It should be noted that the figures are only intended to facilitate the description of the features. The various features described are not intended as an exhaustive description of the subject matter disclosed herein or as a limitation on the scope of the subject matter disclosed herein. Additionally, an illustrated example

need not have all the aspects or advantages shown. An aspect or an advantage described in conjunction with a particular example is not necessarily limited to that example and can be practiced in any other examples even if not so illustrated, or if not so explicitly described. [0059] Furthermore, any element in a claim that does not explicitly state “means for” performing a specified function, or “step for” performing a specific function, is not to be interpreted as a “means” or “step” clause as specified in 35 U.S.C. Section 112, Paragraph 6. In particular, the use of “step of” or “act of” in the Claims herein is not intended to invoke the provisions of 35 U.S.C. 112, Paragraph 6.

[0060] It is noted that, if used, the labels left, right, front, back, top, bottom, forward, reverse, clockwise and counterclockwise have been used for convenience purposes only and are not intended to imply any particular fixed direction. Instead, the labels are used to reflect relative locations and/or directions between various portions of an object.

[0061] Data processing may include data buffering, aligning incoming data from multiple communication lanes, forward error correction (FEC), etc. For example, data may be received by an analog front end (AFE), which can prepare the incoming data for digital processing. The digital portion of the transceivers (e.g., digital signal processor (DSP)) may provide skew management, equalization, reflection cancellation, and/or other functions. It is to be appreciated that the process described herein can provide many benefits, including saving both power and cost.

[0062] Moreover, the terms “system,” “component,” “module,” “interface,” “model,” or the like are generally intended to refer to a computer-related entity, either hardware, a combination of hardware and software, software, or software in execution. For example, a component may be, but is not limited to being, a process running on a processor, a processor, an object, an executable, a thread of execution, a program, and/or a computer. By way of illustration, both an application running on a controller and the controller can be a component. One or more components may reside within a process and/or thread of execution and a component may be localized on one computer and/or distributed between two or more computers.

[0063] Unless explicitly stated otherwise, each numerical value and range may be interpreted as being approximate, as if the word “about” or “approximately” preceded the value of the value or range. Signals and corresponding nodes or ports might be referred to by the same name and are interchangeable for purposes here.

[0064] While embodiments may have been described with respect to circuit functions, the embodiments of the subject matter disclosed herein are not limited. Possible implementations may be embodied in a single integrated circuit, a multi-chip module, a single card, SoC, or a multi-card circuit pack. As would be apparent to one skilled in the art, the various embodiments might also be implemented as part of a larger system. Such embodiments may be employed in conjunction with, for example, a digital signal processor, microcontroller, field-programmable gate array, application-specific integrated circuit, or general-purpose computer.

[0065] As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing blocks in a software program. Such software may be employed in, for example, a digital signal processor, microcontroller, or general-purpose computer. Such software may be embodied in the form of program code embodied in tangible media, such as magnetic recording media, optical recording media, solid-state memory, floppy diskettes, CD-ROMs, hard drives, or any other non-transitory machine-readable storage medium, that when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the subject matter disclosed herein. When implemented on a general-purpose processor, the program code segments combine with the processor to provide a unique device that operates analogously to specific logic circuits. Described embodiments may also be manifest in the form of a bit stream or other sequence of signal values electrically or optically transmitted through a medium, stored magnetic-field variations in a magnetic recording medium, etc., generated using a method and/or an apparatus as described herein.

[0066] A DRAM cache of a device may be used to mask the latency associated with accessing relatively slow media (e.g., NAND storage media). DRAM cache performance can be related to workload characterization, cache parameters, cache eviction algorithms, and other memory management operations. Some systems may use cache with a fixed architecture, where the structure and organization of the cache memory can remain static (e.g., various parameters including, but not limited to, the number of cache lines, set associativity, block size, etc., may be predetermined and cannot be dynamically adjusted based on access patterns or workloads). In some cases, a DRAM cache (e.g., with fixed cache architecture) may use a cache algorithm that is fixed. Cache algorithms can include least recently used (LRU), LRU2Q, most recently used (MRU) algorithm may remove an item that is used the most recently, tiny least frequently used (TinyLFU), three static first in first out (S3-FIFO) cache algorithm that uses FIFO queues to remove objects that are unlikely to be accessed again, and/or apply similar techniques. A cache algorithm can include a cache eviction algorithm and/or a cache replacement algorithm that evicts data from the cache and/or swaps out data when the space is full (e.g., removes a portion of data used the least recently). Based on some systems (e.g., fixed cache systems), there can be limited flexibility in which a suitable eviction/replacement policy may be implemented. In some cases, the eviction/replacement policy and/or associated DRAM cache may not be reconfigurable during runtime (e.g., based on a fixed cache algorithm, based on fixed DRAM cache, etc.). In some cases, performance gains for a system implementing fixed DRAM cache may be limited to a limited number of workloads/applications. Based on the workload characterization of fixed DRAM cache, users may not be allowed to adjust cache algorithms.

[0067] The systems and methods described herein describe cache processor instruction sets that support programmable cache algorithms, which can be used to program memory such as DRAM cache. The systems and methods described herein may be based on an instruction set architecture (ISA). The ISA may include at least one of device control and status registers, cache control and status registers, a command word format, an instruction set, and/or programmable functionality and operation. Based on the systems and methods described herein, a fully programmable ISA may be used to enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, and the like). In some embodiments, ISA execute units that enable programming cache algorithms may be run on cache processor cores. The systems and methods described may include implementing two (or more) separate cache threads based on the design ISA set (e.g., memory request thread, cache eviction thread), which reduces cache processor thread arbitrator overhead. In some embodiments, a set of dedicated ISA for cache algorithms may be used, providing high throughput, low latency, and low implementation cost, while increasing system throughput and decreasing cache latency.

[0068] FIG. 1 illustrates an example system **100** in accordance with one or more implementations as described herein. In FIG. 1, machine **105**, which may be termed a host, a system, or a server, is shown. While FIG. 1 depicts machine **105** as a tower computer, embodiments of the disclosure may extend to any form factor or type of machine. For example, machine **105** may be a rack server, a blade server, a desktop computer, a tower computer, a mini tower computer, a desktop server, a laptop computer, a notebook computer, a tablet computer, etc.

[0069] In some implementations, machine **105** may depict a cache-coherent tiered memory device (e.g., CXL tiered memory device). Machine **105** may include processor **110**, memory **115**, and storage device **120**. Processor **110** may be any variety of processor. It is noted that processor **110**, along with the other components discussed below, are shown outside the machine for ease of illustration: embodiments of the disclosure may include these components within the machine. While FIG. 1 shows a single processor **110**, machine **105** may include any number of processors, each of which may be single core or multi-core processors, each of which may implement a Reduced Instruction Set Computer (RISC) architecture or a Complex Instruction Set Computer

(CISC) architecture (among other possibilities), and may be mixed in any desired combination. [0070] Processor **110** may be coupled to memory **115**. Memory **115** may be any variety of memory, such as flash memory, Dynamic Random Access Memory (DRAM), Static Random Access Memory (SRAM), Persistent Random Access Memory, Ferroelectric Random Access Memory (FRAM), or Non-Volatile Random Access Memory (NVRAM), such as Magnetoresistive Random Access Memory (MRAM), Phase Change Memory (PCM), or Resistive Random-Access Memory (ReRAM). Memory **115** may include volatile and/or non-volatile memory. Memory **115** may use any desired form factor: for example, Single In-Line Memory Module (SIMM), Dual In-Line Memory Module (DIMM), Non-Volatile DIMM (NVDIMM), etc. Memory **115** may be any desired combination of different memory types, and may be managed by memory controller **125**. Memory **115** may be used to store data that may be termed “short-term”: that is, data not expected to be stored for extended periods of time. Examples of short-term data may include temporary files, data being used locally by applications (which may have been copied from other storage locations), and the like.

[0071] Processor **110** and memory **115** may support an operating system under which various applications may be running. These applications may issue requests (which may be termed commands) to read data from or write data to either memory **115** or storage device **120**. When storage device **120** is used to support applications reading or writing data via some sort of file system, storage device **120** may be accessed using device driver **130**. While FIG. **1** shows one storage device **120**, there may be any number (one or more) of storage devices in machine **105**. Storage device **120** may support any desired protocol or protocols, including, for example, the Non-Volatile Memory Express (NVMe®) protocol, a Serial Attached Small Computer System Interface (SCSI) (SAS) protocol, or a Serial AT Attachment (SATA) protocol. Storage device **120** may include any desired interface, including, for example, a Peripheral Component Interconnect Express (PCIe®) interface, or a Compute Express Link (CXL®) interface. Storage device **120** may take any desired form factor, including, for example, a U.2 form factor, a U.3 form factor, a M.2 form factor, Enterprise and Data Center Standard Form Factor (EDSFF) (including all of its varieties, such as E1 short, E1 long, and the E3 varieties), or an Add-In Card (AIC).

[0072] While FIG. **1** uses the term “storage device,” embodiments of the disclosure may include any storage device formats that may benefit from the use of computational storage units, examples of which may include hard disk drives, Solid State Drives (SSDs), or persistent memory devices, such as PCM, ReRAM, or MRAM. Any reference to “storage device” “SSD” below should be understood to include such other embodiments of the disclosure and other varieties of storage devices. In some cases, the term “storage unit” may encompass storage device **120** and memory **115**. Machine **105** may include power supply **135**. Power supply **135** may provide power to machine **105** and its components.

[0073] Machine **105** may include transmitter **145** and receiver **150**. Transmitter **145** or receiver **150** may be respectively used to transmit or receive data. In some cases, transmitter **145** and/or receiver **150** may be used to communicate with memory **115** and/or storage device **120**. Transmitter **145** may include write circuit **160**, which may be used to write data into storage, such as a register, in memory **115** and/or storage device **120**. In a similar manner, receiver **150** may include read circuit **165**, which may be used to read data from storage, such as a register, from memory **115** and/or storage device **120**.

[0074] In the illustrated example, machine **105** may include timer **155**, which may be used to time one or more operations, indicate a time period, indicate a lapse of time, indicate an expiration, indicate a timeout, etc.

[0075] In one or more examples, machine **105** may be implemented with any type of apparatus. Machine **105** may be configured as (e.g., as a host of) one or more of a server such as a compute server, a storage server, storage node, a network server, a supercomputer, data center system, and/or the like, or any combination thereof. Additionally, or alternatively, machine **105** may be configured

as (e.g., as a host of) one or more of a computer such as a workstation, a personal computer, a tablet, a smartphone, and/or the like, or any combination thereof. Machine **105** may be implemented with any type of apparatus that may be configured as a device including, for example, an accelerator device, a storage device, a network device, a memory expansion and/or buffer device, a central processing unit (CPU), a graphics processing unit (GPU), a neural processing unit (NPU), a tensor processing unit (TPU), optical processing units (OPU), and/or the like, or any combination thereof.

[0076] Any communication between devices including machine **105** (e.g., host, computational storage device, and/or any intermediary device) can occur over an interface that may be implemented with any type of wired and/or wireless communication medium, interface, protocol, and/or the like including PCIe, NVMe, Ethernet, NVMe-oF, Compute Express Link (CXL), and/or a coherent protocol such as CXL.mem, CXL.cache, CXL.IO and/or the like, Gen-Z, Open Coherent Accelerator Processor Interface (OpenCAPI), Cache Coherent Interconnect for Accelerators (CCIX), Advanced eXtensible Interface (AXI) and/or the like, or any combination thereof, Transmission Control Protocol/Internet Protocol (TCP/IP), FibreChannel, InfiniBand, Serial ATA Attachment (SATA), Small Computer Systems Interface (SCSI), Serial Attached SCSI (SAS), iWARP, any generation of wireless network including 2G, 3G, 4G, 5G, and/or the like, any generation of Wi-Fi, Bluetooth, near-field communication (NFC), and/or the like, or any combination thereof. In some embodiments, the communication interfaces may include a communication fabric including one or more links, buses, switches, hubs, nodes, routers, translators, repeaters, and/or the like. In some embodiments, system **100** may include one or more additional apparatus having one or more additional communication interfaces.

[0077] Any of the functionality described herein, including any of the host functionality, device functionality, cache processor **140** functionality, and/or the like, may be implemented with hardware, software, firmware, or any combination thereof including, for example, hardware and/or software combinational logic, sequential logic, timers, counters, registers, state machines, volatile memories such as at least one of or any combination of the following: dynamic random access memory (DRAM) and/or static random access memory (SRAM), nonvolatile memory including flash memory, persistent memory such as cross-gridded nonvolatile memory, memory with bulk resistance change, phase change memory (PCM), and/or the like and/or any combination thereof, complex programmable logic devices (CPLDs), field programmable gate arrays (FPGAs), application specific integrated circuits (ASICs) CPUs including CISC processors such as x86 processors and/or RISC processors such as RISC-V and/or ARM processors), GPUs, NPUs, TPUs, OPUs, and/or the like, executing instructions stored in any type of memory. In some embodiments, one or more components of cache processor **140** may be implemented as an SoC.

[0078] In some examples, cache processor **140** may include any one or combination of logic (e.g., logical circuit), hardware (e.g., processing unit, memory, storage), software, firmware, and the like. In some cases, cache processor **140** may perform one or more functions in conjunction with processor **110**. In some cases, at least a portion of cache processor **140** may be implemented in or by processor **110** and/or memory **115**. The one or more logic circuits of cache processor **140** may include any one or combination of multiplexers, registers, logic gates, arithmetic logic units (ALUs), cache, computer memory, microprocessors, processing units (CPUs, GPUs, NPUs, and/or TPUs), FPGAs, ASICs, etc., that enable cache processor **140** to perform functions associated with instruction sets for cache processor (e.g., of tiered memory devices).

[0079] In one or more examples, cache processor **140** may execute one or more commands of a programmable cache instruct set. In some cases, cache processor **140** may receive memory requests (e.g., write request, read request) from a memory controller (e.g., a memory controller that receives commands from a host, an application of the host, etc.) and process the memory requests based on the programmable cache instruct set. In some cases, cache processor **140** may modify one or more aspects of a cache algorithm based on executing a command from the instruction set. For example,

cache processor **140** may replace a first eviction policy with a second eviction policy based on the workload characteristics of an application (e.g., an application generating the memory requests). [0080] FIG. 2 illustrates details of machine **105** of FIG. 1, according to examples described herein. In the illustrated example, machine **105** may include processor **110**. Processor **110** may include one or more processors and/or one or more dies. Processor **110** may include memory controller **125** (e.g., one or more memory controllers) and clock **205** (e.g. one or more clocks), which may be used to coordinate the operations of the components of the machine. Processor **110** may be coupled to memory **115** (e.g., one or more memory chips, stacked memory, etc.), which may include random access memory (RAM), read-only memory (ROM), or other state preserving media, as examples. Processor **110** may be coupled to storage device **120** (e.g., one or more storage devices), and to network connector **210**, which may be, for example, an Ethernet connector or a wireless connector. Processor **110** may be connected to bus **215** (e.g., one or more buses), to which may be attached user interface **220** (e.g., one or more user interfaces) and Input/Output (I/O) interface ports that may be managed using I/O engine **225** (e.g., one or more I/O engines), among other components. As shown, processor **110** may be coupled to cache processor **230**, which may be an example of cache processor **140** of FIG. 1. Additionally, or alternatively, processor **110** may be connected to bus **215**, to which may be attached cache processor **230**.

[0081] FIG. 3 illustrates an example system **300** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of system **300** may be implemented by or in conjunction with cache processor **140** of FIG. 1 and/or cache processor **230** of FIG. 2. In some configurations, one or more aspects of system **300** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0082] In the illustrated example, system **300** may include memory controller **302** (e.g., CXL memory controller), memory response queue **304**, cache processor **306**, memory response queue **308**, cache processor **310**, SRAM **312** (e.g., a shared memory), register file **314**, data controller **316**, DRAM controller **318**, DRAM **320**, NAND controller **322**, and NAND **324**. As shown, SRAM **312** may include system data **346**, ISA code **348**, ISA code **350**, and metadata **352**. The systems and methods described enable a user to program cache algorithms based on cache processor instruction sets. The cache algorithms (e.g., custom cache algorithms) can be downloaded to device memory (e.g., device command memory, memory request queue **304**, memory on cache processor **306**, memory on cache processor **310**, SRAM **312**, DRAM **320**, NAND **324**, etc.). In some cases, device memory can store user programmed scripts based on the cache instruction sets described herein.

[0083] In some examples, a given system may include one or more processors. For example, system **300** may include at least one CPU and/or at least one GPU. The at least one CPU and/or at least one GPU may be in addition to cache processor **306** and/or in addition to cache processor **310**. Accordingly, cache processor **306** and/or cache processor **310** may offload one or more processes from a CPU and/or GPU of a given system (e.g., system **300**). For example, cache processor **306** and/or cache processor **310** may offload one or more cache operations (e.g., processing write requests associated with a cache, processing read requests associated with a cache, programming a cache, configuring a cache, programming one or more cache algorithms, etc.). In some cases, the systems and methods described herein may enable cache algorithms to be modifiable and/or reconfigurable during runtime based at least on cache instruction sets executed by cache processor **306** and/or cache processor **310**.

[0084] With some systems, fixed cache algorithms for DRAM cache restrict the algorithm to some default setting, which limits the applicability to some applications. Some application may perform poorly based on the lack of flexibility with fixed DRAM cache, optimized to the workload of their application. System **300** enables a programmable cache algorithm that may be based on a set of instructions or rules that manage a cache of information associated with a computer program. System **300**, and the associated methods described herein, enable a user to customize cache

algorithms for a given application. Programmable cache algorithms (e.g., eviction/replacement policy) can improve system performance by storing frequently used data in faster memory locations more efficiently. When a cache is full, the cache algorithm can select which data items to remove to make room for new data. Based on the systems and methods described herein, a cache algorithm may be configured for the workloads and characteristics of a given application, improving the cache efficiency associated with execution of that application.

[0085] In some examples, memory controller **302** may depict a CXL memory controller. In some cases, system **300** may depict at least a portion of a tiered memory device (e.g., CXL tiered memory device). CXL tiered memory devices may operate based on device cache. In some cases, the cache may include device DRAM cache (e.g., DRAM **320**). CXL DRAM cache may be part of the compute express link (CXL) technology, which may be based on peripheral component interconnect express (PCIe). CXL DRAM cache can be based on a cache-coherent interconnect protocol that allows processors to communicate with memory expanders and accelerators. The cache may be configured to help mask the latency associated with accessing relatively slow media (e.g., NAND **324**). Based on the systems and methods described herein, performance of DRAM cache such as DRAM **320** can be related to workload characterization, cache parameters, cache eviction algorithms, etc.

[0086] As shown, memory controller **302** may connect to one or more queues. For example, memory controller **302** may connect to memory request queue **304** and/or memory response queue **304**. In some examples, memory controller **302** may be communicatively coupled to a host (e.g., machine **105**, operating system, application of a host, etc.). In some cases, the host may issue a memory request (e.g., read request, write request) to memory controller **302**. Memory controller **302** may add a memory request received from the host to memory request queue **304**. Thus, memory request queue **304** may hold one or more memory requests from memory controller **302**. In conjunction with data controller **316**, cache processor **306** may process the memory requests in memory request queue **304** and provide responses for processed requests to memory response queue **308**. Examples of memory responses provided to memory response queue **308** may include request complete, request canceled, error code for errors encountered, information related to exception handling, data from a processed read request, etc. Memory request queue **304** and/or memory response queue **308** may include a first in first out (FIFO) queue, a last in first out (LIFO) queue, or a first in last out (FILO) queue, and/or some other queue.

[0087] System **300** may include one or more processor cores dedicated to managing device cache (e.g., DRAM **320**) based on instruction sets that enable programmable cache algorithms (e.g., cache algorithms modifiable during runtime based on execution of the instruction sets). In some cases, system **300** may include at least one request cache processor (e.g., cache processor **306**) configured to process memory requests. Additionally, or alternatively, system **300** may include at least one eviction cache processor (e.g., cache processor **310**) configured to process eviction routines (e.g., implementing replacement/eviction policies, evicting items from DRAM **320**, etc.).

[0088] In the illustrated example, cache processor **305** and cache processor **310** include at least one execution unit, at least one GPR, at least one command fetch unit, at least one arbitrator, at least one scheduler, etc. As shown, cache processor **306** may include execution unit **326**, general purpose register (GPR) **328**, command fetch unit **330**, arbitrator **332**, and scheduler **334**. In some cases, execution unit **326** may include an algorithm logic unit (ALU), a load store unit (LSU), and at least one control and status register (CSR). Cache processor **310** may include execution unit **336**, GPR **338**, command fetch unit **340**, arbitrator **342**, scheduler **344**. In some cases, execution unit **326** may include an ALU, an LSU, and at least one CSR.

[0089] GPR **328** and/or GPR **338** may include control registers that hold control data, control messages; status registers that hold information regarding the status of a device, status of a cache, status of a component, etc., interrupt registers to hold information associated with an interrupt or exception, etc. Command fetch unit **330** and/or command fetch unit **340** may fetch a cache

command from command memory (e.g., memory request queue **304**) for processing by execution unit **326** of cache processor **306**. Arbitrator **332** may arbitrate between processes to determine what processes cache processor **306** executes; arbitrator **342** may arbitrate between processes to determine what processes cache processor **310** executes. Scheduler **334** and/or scheduler **334** may prepare data in a register (e.g., GPR **328**, GPR **338**, CSR of a cache processor, register file **314**, etc.) and schedule execution of a cache instruction by a given execution unit. Execution unit **326** and/or execution unit **336** may execute cache instructions described herein. In some cases, execution unit **326** and/or execution unit **336** may include ARM or RISC processors configured for processing cache instruction sets described herein. As shown, execution unit **326** may be associated with processing a memory request thread and execution unit **326** may be associated with processing a cache eviction thread. Execution unit **326** may execute the memory request thread and execution unit **336** may execute the cache eviction thread in parallel.

[0090] SRAM **312** may be configured as a memory that is shared (e.g., shared memory) between cache processor **306** and cache processor **310**. System data **346** may store a cache context for DRAM **320** configured as a cache for system **300**. System data **346** may store a collection of temporary files created by system **300**, which may include system log files, temporary data used to speed up cache system operations, storing frequently accessed information, etc. ISA code **348** may store data, commands, cache instruction sets, etc., associated with cache processor **306** executing a memory request thread. ISA code **350** may store data, commands, cache instruction sets, etc., associated with cache processor **310** executing a cache eviction thread. Metadata **352** may store information associated with data cached in DRAM **320** (e.g., block address, tag, index, block offset, etc.)

[0091] In some cases, register file **314** can include a device control status register and/or cache control status register. For example, register file **314** can include at least one device control status register and/or at least one cache control status register associated with cache instruction sets described herein, which enable programming cache algorithms associated with cache processor **306** executing a memory request thread and/or cache processor **310** executing a cache eviction thread. Additional information regarding device control status registers and cache control status registers can be found in FIGS. **4** and **5** and accompanying description.

[0092] Data controller **316** may control read/write access to DRAM **320** via DRAM controller **318** and/or to NAND **324** via NAND controller **322**. Data of system **300** may generally be stored in NAND **324** (e.g., relatively cheap data storage with sufficient latency). Data that is accessed relatively frequently may be cached in DRAM **320** (e.g., for relatively low latency, high throughput). Data controller **316** may determine whether a read/write request is for DRAM **320** or NAND **324** (e.g., cache hit read/write for DRAM **320**; cache miss read/write for NAND **324**). Data controller **316** may include one or more queues (e.g., DRAM request queue and DRAM response queue for DRAM **320**; NAND request queue and NAND response queue for NAND **324**). Queues of data controller **316** may include FIFOs, LIFOs, FILOs, and/or some other type of queues.

[0093] As shown, cache processor **306** may connect to one or more queues of data controller **316** (e.g., DRAM request queue, DRAM response queue). Cache processor **310** may perform one or more commands from the cache instruction set described herein to execute a memory request thread. Processing a memory request thread may include cache processor **306** processing memory requests fetched from memory request queue **304**. In some cases, cache processor **306** may send read/write requests to data controller **316** (e.g., via a DRAM request queue) for reads/writes to DRAM **320** and/or NAND **324**. Cache processor **306** may determine whether data associated with a memory request is hot data, warm data, cold data based on data access frequency. Based on the cache algorithms being implemented, cache processor **306** may store hot data (e.g., data accessed frequently) in DRAM **320**; warm data (e.g., data accessed frequently, but less frequently than hot data) in DRAM **320** or NAND **324**; and cold data (e.g., data accessed infrequently) in NAND **324**.

[0094] Cache processor **306** may determine whether data associated with a memory request is in

DRAM **320** (e.g., cache hit) or not in DRAM **320** (e.g., cache miss). With a cache hit, cache processor **306** may read the data from DRAM **320** for a read request, or write data to DRAM **320** for a write request (e.g., modify data already in DRAM **320** based on the write request). In some cases, cache processor **306** may access a storage device (e.g., NAND **324**) to process a memory request based on the cache processor **306** determining a state of the data associated with the memory request in relation to the cache and the storage device (e.g., cache miss based on the data being stored in the storage device and not in the cache). With a cache miss, cache processor **306** may read the data from NAND **324** for a read request, or write data to NAND **324** for a write request (e.g., modify data in NAND **324** based on the write request). In some cases, cache processor **310** may receive a request from data controller **316** (e.g., via a NAND memory request queue of data controller **316**) based on the cache miss. Cache processor **310** may perform a cache eviction routine based on a request that cache processor **310** receives from data controller **316**. [0095] As shown, cache processor **310** may connect to one or more queues of data controller **316** (e.g., receive requests from NAND request queue, send responses from NAND response queue). Cache processor **310** may perform one or more commands from the cache instruction set described herein to execute a cache eviction thread. Processing a cache eviction thread may include cache processor **310** processing memory requests fetched from a NAND request queue of data controller **316**. Based on receiving a request, cache processor **310** may execute an eviction action. For example, cache processor **310** may determine to maintain data in DRAM **320** or add data to DRAM **320**. In some cases (e.g., based on a cache miss), cache processor **310** may evict data from DRAM **320** when there is data to add to DRAM **320** and DRAM **320** is full. In some cases, cache processor **310** may send a command to data controller **316** to implement the eviction action (e.g., remove, read, write data to DRAM **320** or NAND **324**).

[0096] With a cache hit, cache processor **306** may execute one or more commands from the cache instruction set described herein. For example, cache processor **306** may receive a read/write request from memory request queue **304**, read metadata **352**, and perform a tag check (e.g., tag load and tag compare) to get a cache hit status for the data associated with the read/write request. Cache processor **306** may send a read/write request to data controller (e.g., to read/write data from/to DRAM **320**) to read/write data associated with the memory request. When data is evicted, cache processor **306** or cache processor **310** may update an eviction status of the data (e.g., dirty status). Cache processor **306** may return to an entry point of the cache request routine for processing a next request. Data controller **316** may issue a response (e.g., to memory response queue **308**) indicating a status of the memory request (e.g., request is completed).

[0097] With a cache miss, cache processor **306** may execute one or more commands from the cache instruction set described herein. For example, cache processor **306** may send a memory request to data controller **316** to read data from or write data to NAND **324**. When data controller **316** receives a response from DRAM controller **318** (e.g., memory request performed), data controller **316** may send a completion signal to memory response queue **308**. Memory controller **302** may provide the response to the host.

[0098] With an eviction routine (e.g., cache processor **310** determines whether to evict data from DRAM **320**), cache processor **306** and/or cache processor **310** may execute one or more commands from the cache instruction set described herein. When DRAM **320** is not full (e.g., cache space available), cache processor **310** may write the data associated with the memory request to DRAM **320**. However, when DRAM **320** is full, then cache processor **310** may remove some of the data in DRAM **320** based on the cache algorithm implemented for that application (LRU, tiny LFU, etc.). Old data (e.g., least recently used data) may be removed from DRAM **320**, and the new data of the memory request may be added to cache. In some cases, the old data may be dirty. Dirty data in the context of a cache can refer to data that has been modified within the cache memory, but which has not yet been written back to the main memory (e.g., DRAM **320** holds an updated version of the data that is not reflected in the original source of the data in NAND **324**). Accordingly, when the

old data being evicted is dirty, then cache processor **310** may read the old data being evicted from DRAM **320** and request data controller **316** to write the evicted data to NAND **324**. When the old data is not dirty (e.g., the old data in cache does not differ from the original source of the old data in NAND), then the old data may be removed from DRAM **320** (e.g., without reading the old data from cache, without writing the old data to the NAND).

[0099] FIG. **4** illustrates an example data structure **400** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of data structure **400** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **400** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0100] In the illustrated example, data structure **400** depicts a configuration associated with one or more device control and status register (CSR). Data structure **400** may enable a user to program cache algorithms based on cache processor instruction sets described herein, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, data structure **400** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.). Device CSRs may handle control and status of a device associated with cache operations described herein (e.g., machine **105**, system **300**, etc.). The control and status information in the device CSRs described herein may be programmable by a user (e.g., customized to a workload of a given application).

[0101] As shown, data structure **400** may include device CSRs **405**, address **410** (e.g., base address) associated with a given device CSR, and description of a given device CSR. Device CSRs **405** may include a device CSR for a memory request thread start address; a device CSR for a cache eviction thread start address; a device CSR for a cache metadata base address; a device CSR for a CXL request status (e.g., CXL controller.fwdarw.memory request thread, for memory request thread polling); a device CSR for a CXL response status (e.g., data controller.fwdarw.CXL controller, for CXL controller polling); a device CSR for a CXL data request status (e.g., memory request thread.fwdarw.data controller, for data controller polling); a device CSR for a NAND data ready status (e.g., data controller.fwdarw.eviction thread, for eviction thread polling); a device CSR for an eviction status (e.g., eviction thread.fwdarw.data controller, for data controller polling); a device CSR for a CXL request queue start address (e.g., low 128 bits for read, high 128 bits for write); a device CSR for a CXL response queue start address (e.g., low 128 bits for read, high 128 bits for write); a device CSR for a DRAM request queue start address (e.g., low 128 bits for read, high 128 bits for write); a device CSR for a DRAM response queue start address (e.g., low 128 bits for read, high 128 bits for write); a device CSR for a NAND request queue start address (e.g., low 128 bits for read, high 128 bits for write); and/or a device CSR for a NAND response queue start address (e.g., low 128 bits for read, high 128 bits for write).

[0102] FIG. **5** illustrates an example data structure **500** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of data structure **500** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **500** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0103] In the illustrated example, data structure **500** depicts a configuration associated with one or more cache control and status register (CSR). Data structure **500** may enable a user to program cache algorithms based on cache processor instruction sets described herein, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, data structure **500** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints,

memory bandwidth constraints, network bandwidth constraints, etc.). Cache CSRs may handle control and status of cache operations described herein, including status of data in cache (e.g., data in DRAM **320**), status of cache (e.g., status of DRAM **320**; cache is full, cache has space for additional data, etc.). The control and status information in the cache CSRs described herein may be programmable by a user (e.g., customized to a workload of a given application).

[0104] As shown, data structure **500** may include cache CSRs **505**, address **510** (e.g., base address) associated with a given cache CSR, and description of a given cache CSR. Device CSRs **505** may include a cache CSR for a CXL memory read/write address (e.g., address of data associated with a memory request); a cache CSR for tag data (e.g., up to 16 ways and 2 set of caches); a cache CSR for cache tags; a cache CSR for a cache index; a cache CSR for a performance profiling registers; a cache CSR for a cache counter (e.g., for tinyLFU cache algorithms); a cache CSR for a cache eviction array; a cache CSR for cache valid metadata (e.g., up to 16 ways and 2 set of caches); a cache CSR for a cache dirty metadata (e.g., up to 16 ways and 2 set of caches); a cache CSR for a CXL request ID (e.g., 0-127 bits, or low 128 bits, for read and 128-256 bits, or high 128 bits, for write); and/or a cache CSR for the number of ways of cache.

[0105] FIG. **6** illustrates an example data structure **600** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0106] In the illustrated example, data structure **600** depicts commands associated with the systems and methods of programmable cache algorithms described herein. Data structure **600** may enable a user to program cache algorithms based on cache processor instruction sets described herein, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, data structure **600** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0107] As shown, data structure **600** may include command code **605**, command name **610**, cycle **615**, and description **620**. Commands of data structure **600** may include a poll command to poll CSRs (e.g., device CSRs of FIG. **4**, cache CSRs of FIG. **5**); a tag load command to load a tag/tag metadata to a tag register (e.g., load multiple tags/tag metadata to tag registers). In some cases, the tag registers may be stored in a tag register region of DRAM **320**, SRAM **312**, registers of cache processor **306**, registers of cache processor **310**, register file **314**, etc. Commands of data structure **600** may include a tag store command to store an updated tag/tag metadata; a tag compare command to compare a CXL tag (e.g., contents of a tag register of a memory request) with one or more cache tags (e.g., contents of one or more tag registers of data stored in cache; data cached in DRAM **320**); a jump compare command to change or jump to a command fetch address; an eviction command to check an eviction queue for an eviction request (e.g., a request queue of data controller **316**) and/or update the eviction queue; a CSR read command to read a cache CSR (e.g., read a cache CSR of FIG. **5**; read cache status; read performance data); and/or a CSR read command to write to a cache CSR (e.g., write a cache CSR of FIG. **5**; write cache status; write performance data).

[0108] As shown, a poll command may take 1 clock cycle to perform (e.g., one clock cycle of a cache processor); a tag load command may take 1 or more clock cycle (e.g., at least 1 clock cycle per tag; one or more clock cycles per multiple tag loads); a tag store command may take 1 or more clock cycle (e.g., at least 1 clock cycle per tag; one or more clock cycles per multiple tag stores); a tag compare command may take 1 or more clock cycle (e.g., at least 1 clock cycle per tag; one or more clock cycles per multiple tag compare); a jump command may take at least 2 clock cycles; an eviction command may take one or more clock cycles; a CSR read command may take 1 clock

cycle; and a CSR write command may take 1 clock cycle.

[0109] FIG. 7 illustrates an example command **700** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **700** may be implemented by or in conjunction with cache processor **140** of FIG. 1 and/or cache processor **230** of FIG. 2. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0110] In the illustrated example, command **700** depicts a format associated with a command of the cache instruction set described herein. Command **700** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **700** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0111] Command **700** may depict a format associated with a poll command of the cache instruction set described herein. In the illustrated example, bits **31:24** may be reserved; bits **23:20** may indicate a number of items in a warm queue; bits **19:16** may indicate a number of items in a hot queue; bits **15:12** may indicate a device CSR queue address (e.g., LRU cache, indicates how many items in a queue); bits **11:8** may indicate a device CSR address (e.g., a request for a device CSR address); bit **7** may indicate a stop setting (e.g., binary 1 indicates stop execution of a cache processor or stop current command, while binary 0 indicates no stop; or vice versa); bits **4-6** may be reserved; and bits **3:0** may indicate the command code for a poll command.

[0112] A cache processor (e.g., cache processor **306**, cache processor **310**) may execute a poll command such as command **700** to poll requests from a memory request queue (e.g., memory request queue **304**). Poll commands such as command **700** may provide an interface between a memory controller and a request cache processor (e.g., memory controller **302** and cache processor **306**). A cache processor may execute a poll command such as command **700** to poll a device CSR (e.g., device CSR of FIG. 4) to verify whether a request ID is valid (e.g., request ID of memory controller **302**, request ID of data controller **316**). A cache processor may execute a poll command, such as command **700**, to copy a request address and ID from a device CSR queue register (e.g., to address and ID registers) when a request status is ready. The address of device CSR queue register may be the combination of a queue base address and the ID from a polled register.

[0113] FIG. 8 illustrates an example command **800** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **800** may be implemented by or in conjunction with cache processor **140** of FIG. 1 and/or cache processor **230** of FIG. 2. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0114] In the illustrated example, command **800** depicts a format associated with a command of the cache instruction set described herein. Command **800** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **800** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0115] Command **800** may depict a format associated with a tag load command of the cache instruction set described herein. In the illustrated example, bits **31:26** may indicate a number of bytes to be loaded (e.g., for a tag load command); bits **25:22** may indicate the number of ways configured for a given cache (e.g., DRAM **320**); bits **21:17** may indicate the bit width of a tag of an item in cache; bits **16:12** may indicate the bit width of an index of an item in cache; bits **11:8** may

indicate a cacheline size of the cache (e.g., a fixed block of memory transferred to a cache at a time). In some examples, binary 0 indicates 64 bytes; binary 1 indicates 128 bytes; binary 2 indicates 256 bytes; binary 3 indicates 384 bytes; binary 4 indicates 512 bytes; binary 5 indicates 640 bytes; binary 6 indicates 768 bytes; binary 7 indicates 896 bytes; binary 8 indicates 1024 bytes; binary 9 indicates 1152 bytes; binary 10 indicates 1280 bytes; binary 11 indicates 1408 bytes; binary 12 indicates 1536 bytes; binary 13 indicates 1664 bytes; binary 14 indicates 1792 bytes; binary 15 indicates 1920 bytes; and binary 15 indicates 2048 bytes. In the illustrated example, bit 7 may indicate main or tiny cache (e.g., binary 0 indicates main cache metadata, binary 1 indicates tiny cache metadata; or vice versa); bits 6:4 may indicate an eviction policy (e.g., eviction policy and/or replacement policy; binary 0 may indicate LRU, binary 1 may indicate LRU2Q, binary 2 may indicate tiny LFU, etc.); and bits 3:0 may indicate the opcode for a tag load command. According to the illustrated example, the eviction policy indicated in command 800, or any command described herein, may indicate up to eight eviction policies (e.g., based on three bits of eviction policy field). Possible eviction policies indicated in a given command may include at least one of: least recently used (LRU), LRU2Q, least frequently used (LFU), tiny LFU, first in first out (FIFO), random replacement (RR), most recently used (MRU), and time to live (TTL), etc.

[0116] A cache processor (e.g., cache processor 306, cache processor 310) may execute a tag load command such as command 800 to monitor the status of a cache (e.g., DRAM 320) and/or the data in the cache. A cache processor may execute a tag load command, such as command 800, to determine whether a memory request is a cache hit or a cache miss. A cache processor may execute a tag load command, such as command 800, to load a tag and/or tag metadata from a memory (e.g., from SRAM 312, from metadata 352) to a tag register. The tag data may include the tag value, a valid indicator (e.g., indicates data in cache for that tag is valid), a dirty indicator (e.g., indicates data in cache for that tag is dirty), eviction array indicator (e.g., indicates data in cache for that tag is in an eviction array, marked for eviction). A memory address associated with a tag may be based on any combination of a device CSR cache metadata address, an eviction policy, an index associated with the tag, and/or CXL memory read/write address. A cache data tag can include a field associated with data in a cache. The tag can identify a cache line and its location in main memory. The tag can be part of a cache address that includes the tag, an index, and/or an offset. A cache can hold multiple items of data. Each item may be associated with its own tag.

[0117] FIG. 9 illustrates an example command 900 in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command 900 may be implemented by or in conjunction with cache processor 140 of FIG. 1 and/or cache processor 230 of FIG. 2. In some configurations, one or more aspects of data structure 600 may be implemented by or in conjunction with machine 105, components of machine 105, or any combination thereof.

[0118] In the illustrated example, command 900 depicts a format associated with a command of the cache instruction set described herein. Command 900 may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command 900 may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0119] Command 900 may depict a format associated with a tag store command of the cache instruction set described herein. In the illustrated example, bits 31:26 may indicate a number of bytes to be stored (e.g., for a tag store command); bits 25:22 may indicate the number of ways configured for a given cache (e.g., DRAM 320); bits 21:17 may indicate the bit width of a tag of an item in cache; bits 16:12 may indicate the bit width of an index of an item in cache; bits 11:8 may indicate a cacheline size of the cache (e.g., a fixed block of memory transferred to a cache at a time; similar possible cacheline sizes to command 800). In the illustrated example, bit 7 may

indicate main or tiny cache (e.g., binary 0 indicates main cache metadata, binary 1 indicates tiny cache metadata; or vice versa); bits **6:4** may indicate an eviction policy (e.g., eviction policy and/or replacement policy; binary 0 may indicate LRU, binary 1 may indicate LRU2Q, binary 2 may indicate tiny LFU, etc.); and bits **3:0** may indicate the opcode for a tag store command.

[0120] A cache processor may execute a tag store command such as command **900** to store a tag and/or tag metadata from a tag register to memory (e.g., to SRAM **312**, to metadata **352**). The tag data may include the tag value, a valid indicator (e.g., indicates data in cache for that tag is valid), a dirty indicator (e.g., indicates data in cache for that tag is dirty), eviction array indicator (e.g., indicates data in cache for that tag is in an eviction array, marked for eviction). A memory address associated with a tag may be based on any combination of a device CSR cache metadata address, an eviction policy, an index associated with the tag, and/or CXL memory read/write address. A cache processor may execute a tag store command, such as command **900**, to store a new tag or store a tag that has been updated. When new data is written to cache, a new tag may be created and stored. When data in cache is accessed (e.g., read or write), a tag for that data may be updated and stored (e.g., loaded, updated, and stored). A tag may be updated to indicate access frequency (e.g., the data was recently accessed in cache), to update an address associated with the data in cache, to update a location of the data in cache, etc.

[0121] FIG. **10** illustrates an example command **1000** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **1000** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0122] In the illustrated example, command **1000** depicts a format associated with a command of the cache instruction set described herein. Command **1000** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **1000** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0123] Command **1000** may depict a format associated with a tag compare command of the cache instruction set described herein. In the illustrated example, bits **31:25** may indicate an immediate value (e.g., a memory address). An immediate value can refer to a constant value that is directly embedded within an instruction itself (e.g., in a tag compare command, in a jump command, etc.). Thus, the value is readily available without needing to be fetched from a register or memory location. In the illustrated example, bits **24:16** may be reserved; bits **15:12** may indicate a device CSR queue register address; bits **11:8** may indicate a device CSR address; bits **7** may be reserved; bits **6:4** may indicate an eviction policy (e.g., eviction policy and/or replacement policy; binary 0 may indicate LRU, binary 1 may indicate LRU2Q, binary 2 may indicate tiny LFU, etc.); and bits **3:0** may indicate the opcode for a tag compare command.

[0124] A cache processor may execute a tag compare command such as command **1000** to compare a CXL tag (e.g., a tag of data associated with a memory request) to one or more tags associated with data in a cache to determine whether there is a match (e.g., cache hit) or no match (e.g., cache miss).

[0125] FIG. **11** illustrates an example command **1100** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **1100** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0126] In the illustrated example, command **1100** depicts a format associated with a command of the cache instruction set described herein. Command **1100** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **1100** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0127] Command **1100** may depict a format associated with a jump command of the cache instruction set described herein. A jump command may be used to alter the sequential flow of program execution by transferring control to a different part of code, which may include jumping to a new memory address specified within the jump command. The jump command may change where execution for a given memory request continues to run. For example, with a cache hit, the execution may continue the memory request routine. With a cache miss, the jump command may be executed to jump to a different address (e.g., jump to an address associated with initiating an eviction routine, etc.).

[0128] In the illustrated example, bits **31:25** may indicate a jump address (e.g., an address associated with a jump command, an address of where to jump to in a memory request routine or cache eviction routine); bits **24:8** may be reserved; bits **7:** may indicate a jump address type (e.g., binary 0 may indicate a relative address, binary 1 may indicate an absolute address; or vice versa); bits **6:4** may be reserved; bits **3:0** may indicate the opcode of a jump command.

[0129] A cache processor may execute a jump command, such as command **1100**, to jump to a specified location of code. A jump command such as command **1100** may include a relative address jump, where the target address is calculated relative to a current location (e.g., current program counter value, current instruction). With a relative jump address, the jump destination may be specified as an offset relative to the current instruction. Additionally, or alternatively, a jump command such as command **1100** may include an absolute address jump, where the jump instruction specifies the exact memory location (e.g., address) where the program execution should transfer to, using a fixed address value, rather than a relative offset or calculated address.

[0130] FIG. **12** illustrates an example command **1200** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **1200** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0131] In the illustrated example, command **1200** depicts a format associated with a command of the cache instruction set described herein. Command **1200** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **1200** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0132] Command **1200** may depict a format associated with an eviction command of the cache instruction set described herein. In the illustrated example, bits **31:25** may indicate an immediate value; bits **24:16** may be reserved; bits **15:12** may indicate a device CSR queue register address; bits **11:8** may indicate a device CSR address; bits **7** may be reserved; bits **6:4** may indicate an eviction policy (e.g., eviction policy and/or replacement policy; binary 0 may indicate LRU, binary 1 may indicate LRU2Q, binary 2 may indicate tiny LFU, etc.); and bits **3:0** may indicate the opcode for an eviction command.

[0133] A cache processor may execute an eviction command, such as command **1200**, to perform one or more tasks of an eviction routine. Based on an instruction from data controller, a cache

processor may execute an eviction command such as command **1200** to check a tag information, find eviction location, initialize an eviction routine, and/or perform an eviction of data from cache based on eviction policy (e.g., eviction policy indicated in command **1200**).

[0134] FIG. **13** illustrates an example command **1300** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **1300** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0135] In the illustrated example, command **1300** depicts a format associated with a command of the cache instruction set described herein. Command **1300** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **1300** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0136] Command **1300** may depict a format associated with a CSR read command of the cache instruction set described herein. In the illustrated example, bits **31:25** may indicate an immediate value (e.g., a memory address); bits **24:16** may be reserved; bits **15:8** may indicate a CSR address (e.g., address of a device CSR, address of a cache CSR); bits **7:4** may be reserved; bits **3:0** may indicate the opcode for a CSR read command.

[0137] A cache processor may execute a CSR read command, such as command **1300**, to read a CSR register (e.g., at the indicated CSR address). A cache processor may execute a CSR read command, such as command **1300**, to store data to memory (e.g., at a memory address indicated in the immediate value). A cache processor may execute a CSR read command, such as command **1300**, to determine a status of the cache system (e.g., machine **105**, system **300**, etc.). A cache processor may execute a CSR read command, such as command **1300**, to debug a cache operation (e.g., of a memory request routine, cache eviction routine) based on reading a CSR.

[0138] FIG. **14** illustrates an example command **1400** in accordance with one or more implementations as described herein. In some configurations, one or more aspects of command **1400** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of data structure **600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof.

[0139] In the illustrated example, command **1400** depicts a format associated with a command of the cache instruction set described herein. Command **1400** may be part of a cache instruction set that enables a user to program cache algorithms, allowing the user to adapt cache algorithms for the workload characteristics of a given application. Thus, command **1400** may enable a fully programmable ISAs that enable various user programmable cache algorithms that are configured according to application constraints (e.g., processing constraints, memory bandwidth constraints, network bandwidth constraints, etc.).

[0140] Command **1400** may depict a format associated with a CSR write command of the cache instruction set described herein. In the illustrated example, bits **31:25** may indicate an immediate value (e.g., a memory address); bits **24:16** may be reserved; bits **15:8** may indicate a CSR address (e.g., address of a device CSR, address of a cache CSR); bits **7:4** may be reserved; bits **3:0** may indicate the opcode for a CSR write command.

[0141] A cache processor may execute a CSR write command, such as command **1400**, to write a CSR register (e.g., at the indicated CSR address). A cache processor may execute a CSR write command, such as command **1400**, to read data from a memory (e.g., at the memory address indicated in the immediate value; read data from memory and write the data to CSR; write control

data and/or system status data read from memory). A cache processor may execute a CSR write command such as command **1400** to store a status of the cache system (e.g., machine **105**, system **300**, etc.). A cache processor may execute a CSR write command, such as command **1400**, to debug a cache operation (e.g., of a memory request routine, cache eviction routine) based on writing to a CSR.

[0142] FIG. **15** depicts a flow diagram illustrating an example method **1500** associated with the disclosed systems, in accordance with example implementations described herein. In some configurations, one or more aspects of method **1500** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of method **1500** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof. The depicted method **1500** is just one implementation and one or more operations of method **1500** may be rearranged, reordered, omitted, and/or otherwise modified such that other implementations are possible and contemplated.

[0143] At **1505**, method **1500** may include receiving, via a first cache processor, a memory request from a memory controller. For example, a first cache processor may receive, from a memory controller, a memory request from a memory controller based on the first cache processor executing a poll command of an instruction set that is configured to program at least one aspect of the cache.

[0144] At **1510**, method **1500** may include determining, via the first cache processor, that data associated with the memory request is stored in the cache. For example, the first cache processor may determine that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with a second cache processor of the cache.

[0145] At **1515**, method **1500** may include processing, via the first cache processor, the memory request. For example, the first processor may process the memory request based on the first processor determining that the data associated with the memory request is stored in the cache (e.g., cache hit).

[0146] FIG. **16** depicts a flow diagram illustrating an example method **1600** associated with the disclosed systems, in accordance with example implementations described herein. In some configurations, one or more aspects of method **1600** may be implemented by or in conjunction with cache processor **140** of FIG. **1** and/or cache processor **230** of FIG. **2**. In some configurations, one or more aspects of method **1600** may be implemented by or in conjunction with machine **105**, components of machine **105**, or any combination thereof. The depicted method **1600** is just one implementation and one or more operations of method **1600** may be rearranged, reordered, omitted, and/or otherwise modified such that other implementations are possible and contemplated.

[0147] At **1605**, method **1600** may include receiving, via a first cache processor, a memory request from a memory controller. For example, a first cache processor may receive, from a memory controller, a memory request from a memory controller based on the first cache processor executing a poll command of an instruction set that is configured to program at least one aspect of the cache.

[0148] At **1610**, method **1600** may include executing at least one tag command of an instruction set to determine that data associated with the memory request is stored in the cache. For example, the first cache processor may execute at least one tag command of an instruction set (e.g., tag load command, tag compare command, tag store command) to determine that data associated with the memory request is stored in the cache (e.g., cache hit).

[0149] At **1615**, method **1600** may include reading data from the cache or modifying data in the cache based on the first cache processor processing the memory request. For example, the first cache processor may read data from the cache based on the first cache processor processing the memory request (e.g., based on the memory request including a read request). The first cache processor may modify data in the cache based on the first cache processor processing the memory

request. For example, based on the memory request including a write request, the first cache processor may write an updated version of data already in the cache.

[0150] In the examples described herein, the configurations and operations are example configurations and operations, and may involve various additional configurations and operations not explicitly illustrated. In some examples, one or more aspects of the illustrated configurations and/or operations may be omitted. In some embodiments, one or more of the operations may be performed by components other than those illustrated herein. Additionally, or alternatively, the sequential and/or temporal order of the operations may be varied.

[0151] Certain embodiments may be implemented in one or a combination of hardware, firmware, and software. Other embodiments may be implemented as instructions stored on a computer-readable storage device, which may be read and executed by at least one processor to perform the operations described herein. A computer-readable storage device may include any non-transitory memory mechanism for storing information in a form readable by a machine (e.g., a computer). For example, a computer-readable storage device may include read-only memory (ROM), random-access memory (RAM), magnetic disk storage media, optical storage media, flash-memory devices, and other storage devices and media.

[0152] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. The terms “computing device,” “user device,” “communication station,” “station,” “handheld device,” “mobile device,” “wireless device” and “user equipment” (UE) as used herein refers to a wired and/or wireless communication device such as a switch, router, network interface controller, cellular telephone, smartphone, tablet, netbook, wireless terminal, laptop computer, a femtocell, High Data Rate (HDR) subscriber station, access point, printer, point of sale device, access terminal, or other personal communication system (PCS) device. The device may be wireless, wired, mobile, and/or stationary.

[0153] As used within this document, the term “communicate” is intended to include transmitting, or receiving, or both transmitting and receiving. Similarly, the bidirectional exchange of data between two devices (both devices transmit and receive during the exchange) may be described as ‘communicating’, when only the functionality of one of those devices is being claimed. The term “communicating” as used herein with respect to wired and/or wireless communication signals includes transmitting the wired and/or wireless communication signals and/or receiving the wired and/or wireless communication signals. For example, a communication unit, which is capable of communicating wired and/or wireless communication signals, may include a wired/wireless transmitter to transmit communication signals to at least one other communication unit, and/or a wired/wireless communication receiver to receive the communication signal from at least one other communication unit.

[0154] Some embodiments may be used in conjunction with various devices and systems, for example, a Personal Computer (PC), a desktop computer, a mobile computer, a laptop computer, a notebook computer, a tablet computer, a server computer, a handheld computer, a handheld device, a Personal Digital Assistant (PDA) device, a handheld PDA device, an on-board device, an off-board device, a hybrid device, a vehicular device, a non-vehicular device, a mobile or portable device, a consumer device, a non-mobile or non-portable device, a wireless communication station, a wireless communication device, a wireless Access Point (AP), a wired or wireless router, a wired or wireless modem, a video device, an audio device, an audio-video (A/V) device, a wired or wireless network, a wireless area network, a Wireless Video Area Network (WVAN), a Local Area Network (LAN), a Wireless LAN (WLAN), a Personal Area Network (PAN), a Wireless PAN (WPAN), and the like.

[0155] Some embodiments may be used in conjunction with one way and/or two-way radio communication systems, cellular radio-telephone communication systems, a mobile phone, a cellular telephone, a wireless telephone, a Personal Communication Systems (PCS) device, a PDA

device which incorporates a wireless communication device, a mobile or portable Global Positioning System (GPS) device, a device which incorporates a GPS receiver or transceiver or chip, a device which incorporates an RFID element or chip, a Multiple Input Multiple Output (MIMO) transceiver or device, a Single Input Multiple Output (SIMO) transceiver or device, a Multiple Input Single Output (MISO) transceiver or device, a device having one or more internal antennas and/or external antennas, Digital Video Broadcast (DVB) devices or systems, multi-standard radio devices or systems, a wired or wireless handheld device, e.g., a Smartphone, a Wireless Application Protocol (WAP) device, or the like.

[0156] Some embodiments may be used in conjunction with one or more types of wireless communication signals and/or systems following one or more wireless communication protocols, for example, Radio Frequency (RF), Infrared (IR), Frequency-Division Multiplexing (FDM), Orthogonal FDM (OFDM), Time-Division Multiplexing (TDM), Time-Division Multiple Access (TDMA), Extended TDMA (E-TDMA), General Packet Radio Service (GPRS), extended GPRS, Code-Division Multiple Access (CDMA), Wideband CDMA (WCDMA), CDMA 2000, single-carrier CDMA, multi-carrier CDMA, Multi-Carrier Modulation (MDM), Discrete Multi-Tone (DMT), Bluetooth™, Global Positioning System (GPS), Wi-Fi, Wi-Max, ZigBee™, Ultra-Wideband (UWB), Global System for Mobile communication (GSM), 2G, 2.5G, 3G, 3.5G, 4G, Fifth Generation (5G) mobile networks, 3GPP, Long Term Evolution (LTE), LTE advanced, Enhanced Data rates for GSM Evolution (EDGE), or the like. Other embodiments may be used in various other devices, systems, and/or networks.

[0157] Although an example processing system has been described above, embodiments of the subject matter and the functional operations described herein can be implemented in other types of digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them.

[0158] Embodiments of the subject matter and the operations described herein can be implemented in digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. Embodiments of the subject matter described herein can be implemented as one or more computer programs, i.e., one or more components of computer program instructions, encoded on computer storage medium for execution by, or to control the operation of, information/data processing apparatus. Alternatively, or in addition, the program instructions can be encoded on an artificially-generated propagated signal, for example a machine-generated electrical, optical, or electromagnetic signal, which is generated to encode information/data for transmission to suitable receiver apparatus for execution by an information/data processing apparatus. A computer storage medium can be, or be included in, a computer-readable storage device, a computer-readable storage substrate, a random or serial access memory array or device, or a combination of one or more of them. Moreover, while a computer storage medium is not a propagated signal, a computer storage medium can be a source or destination of computer program instructions encoded in an artificially-generated propagated signal. The computer storage medium can also be, or be included in, one or more separate physical components or media (for example multiple CDs, disks, or other storage devices).

[0159] The operations described herein can be implemented as operations performed by an information/data processing apparatus on information/data stored on one or more computer-readable storage devices or received from other sources.

[0160] The term “data processing apparatus” encompasses all kinds of apparatus, devices, and machines for processing data, including by way of example a programmable processor, a computer, a system on a chip, or multiple ones, or combinations, of the foregoing. The apparatus can include special purpose logic circuitry, for example an FPGA (field programmable gate array) or an ASIC (application-specific integrated circuit). The apparatus can also include, in addition to hardware,

code that creates an execution environment for the computer program in question, for example code that constitutes processor firmware, a protocol stack, a database management system, an operating system, a cross-platform runtime environment, a virtual machine, or a combination of one or more of them. The apparatus and execution environment can realize various different computing model infrastructures, such as web services, distributed computing and grid computing infrastructures.

[0161] A computer program (also known as a program, software, software application, script, or code) can be written in any form of programming language, including compiled or interpreted languages, declarative or procedural languages, and it can be deployed in any form, including as a stand-alone program or as a component, component, subroutine, object, or other unit suitable for use in a computing environment. A computer program may, but need not, correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or information/data (for example one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (for example files that store one or more components, sub-programs, or portions of code). A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

[0162] The processes and logic flows described herein can be performed by one or more programmable processors executing one or more computer programs to perform actions by operating on input information/data and generating output. Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and information/data from a read-only memory or a random access memory or both. The essential elements of a computer are a processor for performing actions in accordance with instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive information/data from or transfer information/data to, or both, one or more mass storage devices for storing data, for example magnetic, magneto-optical disks, or optical disks. However, a computer need not have such devices. Devices suitable for storing computer program instructions and information/data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, for example EPROM, EEPROM, and flash memory devices; magnetic disks, for example internal hard disks or removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0163] To provide for interaction with a user, embodiments of the subject matter described herein can be implemented on a computer having a display device, for example a CRT (cathode ray tube) or LCD (liquid crystal display) monitor, for displaying information/data to the user and a keyboard and a pointing device, for example a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, for example visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input. In addition, a computer can interact with a user by sending documents to and receiving documents from a device that is used by the user; for example, by sending web pages to a web browser on a user's client device in response to requests received from the web browser.

[0164] Embodiments of the subject matter described herein can be implemented in a computing system that includes a back-end component, for example as an information/data server, or that includes a middleware component, for example an application server, or that includes a front-end component, for example a client computer having a graphical user interface or a web browser through which a user can interact with an embodiment of the subject matter described herein, or

any combination of one or more such back-end, middleware, or front-end components. The components of the system can be interconnected by any form or medium of digital information/data communication, for example a communication network. Examples of communication networks include a local area network (“LAN”) and a wide area network (“WAN”), an inter-network (for example the Internet), and peer-to-peer networks (for example ad hoc peer-to-peer networks). [0165] The computing system can include clients and servers. A client and server are generally remote from each other and typically interact through a communication network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other. In some embodiments, a server transmits information/data (for example an HTML page) to a client device (for example for purposes of displaying information/data to and receiving user input from a user interacting with the client device). Information/data generated at the client device (for example a result of the user interaction) can be received from the client device at the server.

[0166] While this specification contains many specific embodiment details, these should not be construed as limitations on the scope of any embodiment or of what may be claimed, but rather as descriptions of features specific to particular embodiments. Certain features that are described herein in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable sub-combination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a sub-combination or variation of a sub-combination.

[0167] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

[0168] Thus, particular embodiments of the subject matter have been described. Other embodiments are within the scope of the following claims. In some cases, the actions recited in the claims can be performed in a different order and still achieve desirable results. In addition, the processes depicted in the accompanying figures do not necessarily require the particular order shown, or sequential order, to achieve desirable results. In certain embodiments, multitasking and parallel processing may be advantageous.

[0169] Many modifications and other examples as set forth herein will come to mind to one skilled in the art to which these embodiments pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the embodiments are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

Claims

1. A method of programmable cache algorithms, the method comprising: receiving, from a memory controller, a memory request based on a first cache processor of a cache executing a poll command of an instruction set that is configured to program at least one aspect of the cache in association

with at least one of a cache memory control and status register (CSR) or a device CSR; determining that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with a second cache processor of the cache; and processing, via the first cache processor, the memory request based on determining that the data associated with the memory request is stored in the cache.

2. The method of claim 1, wherein processing the memory request comprises the first cache processor reading the data associated with the memory request from the cache based on the memory request including a read request.
3. The method of claim 1, wherein processing the memory request comprises the first cache processor modifying the data that is in the cache and associated with the memory request based on the memory request including a write request.
4. The method of claim 1, wherein processing the memory request comprises the first cache processor executing a tag load command of the instruction set to load a tag of data in the cache to a tag register, executing a tag compare command of the instruction set to compare the tag of the data in the cache to a tag of the data associated with the memory request, updating an access frequency attribute of the tag of the data in the cache, and executing a tag store command of the instruction set to store, in the metadata of the shared memory, the updated tag of the data in the cache.
5. The method of claim 1, further comprising determining a memory address of the data associated with the memory request based on the first cache processor querying the cache CSR.
6. The method of claim 1, wherein the first cache processor querying the metadata is based on the first cache processor querying the device CSR for an address of the metadata.
7. The method of claim 1, wherein the first cache processor executing the poll command of the instruction set is based on the first cache processor querying the device CSR for a starting address of a cache request routine.
8. The method of claim 1, further comprising accessing, via the first cache processor, a storage device to process the second memory request, the storage device being accessed based on the first cache processor determining a state of data associated with a second memory request in relation to the cache and the storage device.
9. The method of claim 8, wherein processing the memory request comprises the first cache processor writing data to the storage device based on the second memory request including a second write request or reading data from the storage device based on the second memory request including a second read request.
10. The method of claim 8, wherein processing the second memory request comprises the first cache processor executing a tag load command of the instruction set to load a tag of data in the cache to a tag register, executing a tag compare command of the instruction set to compare the tag of data in the cache to a tag of the data associated with the second memory request.
11. The method of claim 8, wherein processing the second memory request comprises the second cache processor: determining that the cache includes available space to store the data associated with the second memory request based on the second cache processor querying the cache CSR for a status of the cache; copying the data associated with the second memory request from a storage device to the cache based on the second memory request including a read request or writing the data associated with the second memory request to the cache based on the second memory request including a write request; and executing a tag store command of the instruction set to store, in the metadata of the shared memory, a tag of the data associated with the second memory request.
12. The method of claim 8, wherein processing the second memory request comprises the second cache processor: determining that the cache is full based on the second cache processor querying the cache CSR for a status of the cache; evicting a portion of data from the cache based on the second cache processor implementing an eviction policy that the second cache processor indicates in at least one command of the instruction set; and writing the portion of data evicted from the cache to a storage device based on the second cache processor determining a mismatch between the

portion of data evicted from the cache and data in the storage device associated with the portion of data evicted from the cache.

13. The method of claim 1, wherein: the instruction set is implemented on a cache-coherent tiered memory device that comprises the memory controller, the cache, the first cache processor, the second cache processor, and a storage device, the cache comprises a dynamic random-access memory, and the storage device comprises a NAND storage device.

14. A cache device, comprising: a cache; a storage device; a memory controller; a first cache processor; and a second cache processor, wherein: the memory controller is configured to receive a memory request based on the first cache processor executing a poll command of an instruction set that is configured to program at least one aspect of the cache in association with at least one of a cache control and status register (CSR) or a device CSR; the first cache processor is configured to determine that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with the second cache processor; and the first cache processor is configured to process the memory request based on determining that the data associated with the memory request is stored in the cache.

15. The cache device of claim 14, wherein the first cache processor processing the memory request comprises the first cache processor reading the data associated with the memory request from the cache based on the memory request including a read request.

16. The cache device of claim 14, wherein the first cache processor processing the memory request comprises the first cache processor modifying the data that is in the cache and associated with the memory request based on the memory request including a write request.

17. The cache device of claim 14, wherein the first cache processor processing the memory request comprises the first cache processor executing a tag load command of the instruction set to load a tag of data in the cache to a tag register, executing a tag compare command of the instruction set to compare the tag of the data in the cache to a tag of the data associated with the memory request, updating an access frequency attribute of the tag of the data in the cache, and executing a tag store command of the instruction set to store, in the metadata of the shared memory, the updated tag of the data in the cache.

18. The cache device of claim 14, further comprising the first cache processor being configured to determine a memory address of the data associated with the memory request based on the first cache processor querying the cache CSR.

19. A non-transitory computer-readable medium storing code that comprises instructions executable by a first cache processor to: receive, from a memory controller, a memory request based on the first cache processor executing a poll command of an instruction set that is configured to program at least one aspect of a cache in association with at least one of a cache control and status register (CSR) or a device CSR; determine that data associated with the memory request is stored in the cache based on the first cache processor querying a metadata of a shared memory that is shared with a second cache processor of the cache; and process the memory request based on determining that the data associated with the memory request is stored in the cache.

20. The non-transitory computer-readable medium of claim 19, wherein the first cache processor processing the memory request comprises the first cache processor reading the data associated with the memory request from the cache based on the memory request including a read request.
