Computing with Chunks

by

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Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

Doctor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2013

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Abstract

Modern computing substrates like general-purpose GPUs, massively multi-core processors, and cloud computing clusters offer practically unlimited resources at the cost of requiring programmers to manage those resources for correctness, efficiency, and performance. Instead of using generic abstractions to write their programs, programmers of modern computing substrates are forced to structure their programs around available hardware. This thesis argues for a new generic machine abstraction, the Chunk Model, that explicitly exposes program and machine structure, making it easier to program modern computing substrates.

In the Chunk Model, fixed-sized chunks replace the flat virtual memories of traditional computing models. Chunks may link to other chunks, preserving the structure of and important relationships within data and programs as an explicit graph of chunks. Since chunks are limited in size, large data structures must be divided into many chunks, exposing the structure of programs and data structures to run-time systems. Those run-time systems, in turn, may optimize run-time execution, both for ease of programming and performance, based on the exposed structure.

This thesis describes a full computing stack that implements the Chunk Model. At the bottom layer is a distributed chunk memory that exploits locality of hardware components while still providing programmer-friendly consistency semantics and distributed garbage collection. On top of the distributed chunk memory, we build a virtual machine that stores all run-time state in chunks, enabling computation to be distributed through the distributed chunk memory system. All of these features are aimed at making it easier to program modern computing substrates.

This thesis evaluates the Chunk Model through example applications in cloud computing, scientific computing, and shared client/server computing.

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Acknowledgments

During my quixotic journey through graduate school, I have been fortunate to have the support of many caring and loving people. First, I would like to thank my advisor, Steve Ward, for his advice and encouragement during my long tenure as a graduate student. Steve's many design and architecture insights helped shape the both the big picture ideas and the implementation details of my thesis project. He has also helped me grow as an engineer and as a scientist.

I acknowledge my thesis committee members, Anant Agarwal and Sam Madden, for providing me with clear advice on how to clarify and improve my thesis. I appreciate all of the warm advice Chris Terman has given me over the years, first as my undergraduate advisor and later as a colleague. I also thank Cree Bruins for all of her help in fighting MIT's bureaucracy; I hope I have not caused too many problems!

I am deeply indebted to Hubert Pham for his continual help not only with my thesis project, but also for being a close friend always willing to hear and help resolve complaints and rants. I would not have been able to take on as many projects as I have in graduate school without Hubert's help.

I have been fortunate to work with many brilliant minds as project co-conspirators and co-authors while at MIT: Christian Becker, Grace Chau, Brent Lagesse, Umar Saif, Gregor Schiele, Chris Stawarz, Jacob Strauss, Jason Waterman, Eugene Weinstein, Victor Williamson, and Fan Yang. I thank each of them for their input and expertise.

I thank my family for being my foundation and for their emotional support. To my mom, thank you for teaching me to love learning and providing me with tools to succeed in life. To my sister, thank you for showing me how to persevere though tough situations. To my grandfather, thank you for always encouraging me. Finally, to Trisha, my partner in life, I love you and thank you for growing with me as we both wound our ways through MIT.

This work was sponsored by the T-Party Project, a joint research program between MIT and Quanta Computer Inc., Taiwan. Portions of this thesis were previously published at IEEE PerCom [77], at HotOS [80], at ACM MCS [78], and in *Pervasive and Mobile Computing* [79]. The video frames used in Figures 2.1, 2.5, and 6.1 come from *Elephants Dream* [59] and are used under the Creative Commons Attribution license.

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Chapter 1

Introduction

In the past few years, the computer industry has seen the growth of three new computing substrates: elastic cloud computing, massively multi-core computing, and general-purpose GPU computing. At a high-level, these three substrates are wildly different. Elastic cloud computing systems like Amazon's EC2 [8] and Microsoft's Azure [70] provide dynamically expandable clusters of hosts, each connected over a virtualized network. Massively multi-core processors like the Tilera TILE [91] series of processors provide a plethora of processor cores connected by on-chip buses and local caches. General-purpose GPUs like NVIDIA's Tesla [64] provide an abundance of ALUs connected by a hierarchy of memories.

While the granularity and specifics of these new substrates differ, what is common to all of them is (1) an abundance of processing elements and (2) programmer-visible communication and storage hierarchies whose proper utilization determines both correctness and performance of applications. For example, in the cloud, intra-core operations are faster than intra-host operations, which are faster than inter-host operations. Likewise, in the GPU, communication and data sharing within a single processing element is fast compared to communication and sharing processing between elements, which itself is fast compared to CPU to GPU communication.

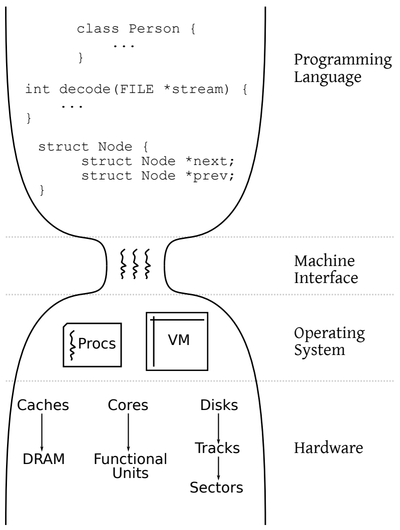
In contrast to "normal" CPU-based platforms that automatically manage the memory and communication hierarchy for correctness and high performance, programmers must carefully manage the communications and storage hierarchies of the new computing substrates so that processing elements are continually fed with instructions and data. Typically this is done by manually managing communication and data placement with substrate-specific frameworks to ensure that related computations are on processing elements close to each other in the computing substrate and that computations "fit" into the variously sized storage buckets that each level of the substrate provides. The substrate-specific frameworks force programmers to use special programming paradigms that chain their programs to particular configurations of specific machines. This is unfortunate because it takes flexibility away from programmers by restricting how they may solve their problems.

1.1 Program Structure versus Platform Structure

To better understand the predicament of modern computing substrates, it is instructive to review how software and hardware are structured and how they work together. At the programming-language layer, programmers use structuring mechanisms provided by their favorite language to construct models of the real-world problems they need to solve. For example, all programming languages provide functions to organize algorithms and control execution of code as well as record types to organize related data. Functions can be further decomposed into basic blocks connected by explicit flow control primitives. Object-oriented languages extend the model by providing objects that tie code and related methods together. At this top-layer, programming language structuring mechanisms allow programmers to optimize for maintainability and readability of code by keeping related concepts near each other in source code—leading to locality of concepts in the program source—as well as build layers of abstraction that hide unnecessary details that would otherwise hinder understanding of the program.

Explicit structure is also rich at the hardware layer. At this level, structure reflects finite physical resources with different performance characteristics, sizes, and availability. For example, memory is organized into a hierarchy of fast and small caches spilling over into multi-channel DRAM main-memories, all backed by slow, but potentially enormous, disks and network file systems. Data that are in the same cache will be equally fast to access, while those that are in different levels of the hierarchy will have slower access times. A program whose working set can fit within a high-speed cache will be orders of magnitude faster than a program that must go out to main memory, or worse yet, swap. Similarly, computation power is organized into threads that execute on particular cores embedded within a heterogeneous communication topology. Two threads assigned to the same processor or chip package will be able to more easily communicate and synchronize than two threads in cores in different places on the network. Similarly, threads on the same network will be able to more easily communicate and synchronize compared to threads that must communicate over the wide-area Internet. In general, the closer two related items are to each other in the memory or processor network, the faster the application will be able to combine and use the items. However, cost and power concerns constrain the fast components to be small relative to the rest of the system, forcing the application and operating system to continually copy data into and out of the fast components in order to maintain high performance. Ergo, the hardware has a natural, if non-linear, "distance" metric between components.

In contrast, the middle of the computing stack—the machine abstraction consisting of machine code instructions operating on a flat address space of memory—is largely devoid of explicit structure. Programs are compiled into strings of instructions that operate in a flat virtual memory address space on flattened data structures. The flat address space obscures the relationship between parts of a program to the operating system: because there is no requirement to keep related code and data close to each other, they are often scattered throughout the address space. Even if related code and data were in similar locations, the lack of explicit typing of data in memory makes it difficult to divine exact relationships since the processor cannot distinguish pointers from integers until it uses them [26]. The



```
     class Person {
         ...
     }

int decode(FILE *stream) {
    ...
}

 struct Node {
      struct Node *next;
      struct Node *prev;
 }
```

Figure 1.1: The structural hourglass of computing.

flat address space also obscures from the program the costs of different data structures and code organizations since the machine model offers no portable way of exposing the sizes, and consequently, the predicted placement or fragmentation of objects within the hardware components in the system. As Figure 1.1 illustrates, the machine abstraction forms the structural bottleneck between the highly structured ends of hardware and software.

1.2 Mapping Structure

Since compute resources are of finite size and there is a cost associated with moving data between different components of the machine, a key problem in maintaining high performance in a computer system is ensuring that related parts of a program are located "close" to each other. When resource characteristics and limits are known, e.g., exactly how big a component can get before it overflows a level in the storage hierarchy or exactly how close two related threads of computation need to be to maintain high performance, programmers can build systems that exploit resources efficiently. For example, once a spinning hard disk has positioned its disk read head over a track, it can read or write the entire track at very high speed, but will not be able to perform any reads or writes while moving (seeking) the head to another track. As such, file systems have evolved to collect many small reads and writes and coalesce them into a single large read or write to avoid costly head seeks.

1.2.1 Optimization within the Flat Middle

Given that both programs and computers are highly structured, we would like to cast the locality problem to one of mapping program structure onto machine structure, ideally in a machine-portable way. Unfortunately, the unstructured machine abstraction makes the mapping harder since program structure is obscured by the implicit structure of machine code and the machine's structure is obscured by the flat memory address space. Indeed, it is because of how the traditional machine abstraction obscures structure that modern computing substrates each come with their own frameworks and structuring abstractions.

The design choice to connect two highly structured layers with an unstructured intermediary layer made sense at one time because the two layers have orthogonal structure and could be engineered independently. Indeed, for the past several decades, computer scientists and engineers have been able to build elegant optimizations at each end of our hourglass that provided acceptable performance despite the thin middle. At the hardware-level, caches trace program execution and place commonly used code and data in fast memory banks close to the processor, essentially dynamically extracting “close” code and data from patterns in the memory access stream. At the software layer, optimizing compilers remove unnecessary structure from applications by putting related code in the same basic blocks. The flattened code essentially groups related functions into sequential streams of instructions, better matching the cache-enhanced flat execution environment by enabling address-based caches to pre-fetch more related data.

1.2.2 Breaking the Abstraction

These optimizations, however, can only extract so much structure from the executing program. As computers evolved, simple caches and hardware-agnostic optimizations were no longer good enough to fully utilize new hardware and the industry resorted to breaking through the clean machine code abstraction.

For example, in the early 1990’s compilers were tuned for the pipelines, delay slots, and cache configuration for specific processors [22, 93], leaking specific hardware details through the machine language abstraction up to the program and, consequently, pairing binaries to specific implementation details of particular machines. Recent work on cache-oblivious algorithms and data structures [37] has reduced the need to worry about the specifics of any cache—though cache-oblivious algorithms do assume that there is some hierarchy in the memory system. Demaine [30] surveys early work in the area and shows that for many problems, cache-oblivious algorithms can meet the theoretical running times of cache-aware algorithms. Unfortunately, cache-oblivious algorithms require program code to be structured in a particular way that limits how programmers may implement their algorithms.

Similarly, very long instruction word (VLIW) processors [35] expose all of the functional units in the processor directly to the user program and require the user program (or compiler) to schedule everything. VLIW failed in the marketplace for two reasons. First, each VLIW processor had a different number of functional units, and as such required different binaries for each generation of the same processor family, reducing portability.

Second, compilers could not statically fill functional units any better than normal superscalar processors.

1.2.3 Dissolving the Machine Abstraction

The systems of the previous section all break the machine abstraction by exposing low-level information to the highest levels of the computation stack, where it was believed that a compiler could make the most use of the extra information. However, these fix-ups are unsuccessful because there is only so much optimization that can be applied to the instruction stream of a single program. As the computing environment continues to evolve, we may be faced with problems that may not be solvable by simply considering a single stream of instructions, but rather may require a more holistic approach to how applications are structured and how they may interact with increasingly complex machines. For example:

- Users increasingly interact with video and other streaming media that passes through the processor once, suffering high memory latencies to bring data into the processor as well as polluting the cache with now-stale data. The program may work more efficiently if the processor pre-fetches data into a reserved subset of cache lines while leaving other lines alone. In order to do so, we need a way to analyze the structure of the streaming media application and have a run-time system schedule memory reads ahead of the application.

- As processor frequency scaling has hit a power-induced limit, we have seen a resurgence in distributed and parallel computing. In the flat model, the program must manage its own execution and manage the lifetime of threads. Programmers would be far more efficient if the system could identify program areas that may potentially run in parallel and use that information to automatically manage thread pools for the application.

- Many modern applications also make use of computing clusters that scatter parts of the application across many machines. Is there a way to allow a run-time system to optimize placement of components based on the dynamic needs of applications?

In all of these cases, the application may be able to run more efficiently if the operating system can more easily analyze the structure of the application and use this information to schedule resources proactively. Rather than add more features to our existing machine abstraction, it might make sense to have a new abstraction that takes into account the need for run-time optimization by the operating system.

1.3 Thesis: A Structured Computing Model

This thesis explores the hypothesis that preserving and exposing structural information about both software and hardware across the machine abstraction will make it easier to build and maintain broad classes of applications running on modern computing substrates. Rather than design ad-hoc APIs that cater to specific problem domains and application designs, we would like a new abstraction that exposes relevant structure in a way that run-time support software can leverage to manage and optimize applications, yet itself is application-generic and machine-generic. In other words, we explore whether expanding the thin middle in the structural hourglass of Figure 1.1 makes it easier to build application-generic supporting layers for the variety of modern computing substrates.

1.3.1 Principles

The design of the abstractions and mechanisms detailed in this thesis are guided by two core principles influenced by the observations of the previous few sections:

Structural Transparency Our primary hypothesis is that an abstract notion of structure will enable run-time systems to automatically and efficiently map program structure onto the machine structure of modern computing substrates. When structure is transparent to the runtime, it provides a foundation on which to exploit structure for efficiency and optimization. As such, our abstractions and mechanisms should be designed to make structure explicit.

Structural Navigability The exposed structure encouraged by the Structural Transparency principle is only useful if the structures are logically laid out. A data structure whose interior details seem randomly designed will be harder to exploit than one where related information is localized within containers, where paths to required data are clear-cut, and where there are obvious contours for sub-setting the data structure to make its run-time footprint smaller.

Structural Navigability is the principle that computation should be able to efficiently navigate through a data structure to access and manipulate only the parts relevant to the computation at hand, while ignoring those parts that are irrelevant. The abstractions and mechanisms we provide must encourage developers to employ those abstractions to express relations and locality that may otherwise be lost in translation between the program layer and the machine layer.

The Structural Navigability and Structural Transparency principles build upon each other, as optimizations that exploit Structural Navigability depend on Structural Transparency as a foundation. At the same time, those optimizations may remove negative performance impacts of Structural Transparency, thus encouraging developers to refactor existing data structures into more finely-grained data structures and potentially enabling another round of Structural Navigability-based optimization.

1.3.2 Contributions

This thesis makes two major technical contributions: the Chunk Model, an application-generic, platform-generic, structure-preserving memory model, and the Chunk Platform, a prototype implementation of the Chunk Model.

The Chunk Model

This thesis explores our hypothesis through the Chunk Model, a structure-preserving memory model. In the Chunk Model, memory comprises a universe of individually-identified, fixed-sized *chunks*. The Chunk Model does not have an address space: instead chunks reference other chunks with explicitly-marked links containing the identifiers of other chunks. Applications express their multidimensional data structures as graphs of explicitly linked chunks rather than flattened data structure connected by implicit address pointers.

We chose the Chunk Model to explore application- and platform-generic structuring mechanisms for three reasons. First, graphs of chunks are generic enough to build any pointer-based data structure. Applications using the Chunk Model only need to translate

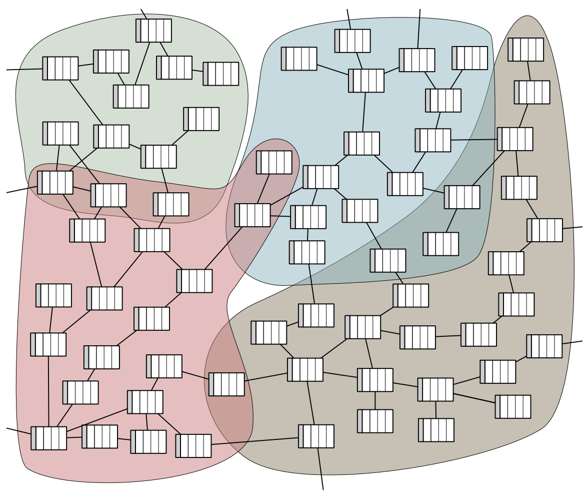


Figure 1.2: A universe of chunks divided into finite subsets. Each subset may be hosted by independent machines. Note that some links extend beyond the borders of the figure.

their internal structures to chunk-based ones, rather than use platform-specific structuring primitives. Second, the Chunk Model forces objects larger than one chunk to be expressed as graphs of chunks. In doing so, the application explicitly exposes its structures to run-time layers, enabling those run-time layers to optimize execution of the chunk-based applications using information in the chunk graph. Third, the use of identities rather than addresses insulates the Chunk Model from the constraints of any platform-specific addressing scheme. As shown in Figure 1.2, it is possible to divide the universe into bounded, potentially shared, subsets of chunks distributed among independent hardware nodes. While a particular piece of hardware may only be able to access its finite subset of the universe of chunks at any given time, clever management and translation of "universal identities" to local identifiers ensure that nodes using the Chunk Model may migrate chunks between themselves, enabling each node to have a finite window on the infinite universe of chunks.

The Chunk Platform

The Chunk Platform implements the Chunk Model while embracing the distributed and network-oriented nature of modern computing substrates. Each node in the Chunk Platform runs a node-local Chunk Runtime that manages the chunk-based applications on the node and provides those applications with a Chunk API that give them a window into the universe of shared chunks.

The Chunk Runtime on each node can only hold a subset of the shared universe of chunks. To give applications access to the whole universe of chunks, the Chunk Runtime on each node uses a low-level networking protocol called the Chunk Exchange Protocol to manage the distribution of chunks. The Chunk Exchange Protocol enables nodes to divvy up the universe of chunks among Chunk Runtimes, as illustrated by Figure 1.2. The Chunk Runtime uses the Chunk Exchange Protocol to take care of coherent caching of chunks, consistent updates to chunk copies, and reclamation of chunks as computations no longer need them. The Chunk Exchange Protocol uses Reference Trees, an abstraction introduced by Halstead [47], to manage chunks distributed across multiple Chunk Runtimes. Reference Trees abstract and summarize the configuration of the distributed chunk universe in a way that reduces the amount of local state each Chunk Runtime must maintain. Reference Trees also provide convenient mechanisms for maintaining consistency of chunk updates as well as for garbage collection of chunk resources.

The Chunk Platform serves as a prototyping platform to evaluate and validate the Chunk Model. As such, the Chunk Platform supports a variety of applications ranging from those that use chunks only as a distributed data store to SCVM, a virtual machine architecture that uses the Chunk Model for computation.

Other Contributions

While we primarily use the Chunk Platform to evaluate the Chunk Model, our implementation of the Chunk Platform provides several other contributions:

- a wire format for sharing graphs of chunks,
- a distributed protocol implementing a sequentially consistent memory model for shared graphs of chunks,
- a distributed garbage collection algorithm of chunk graphs that can collect cycles distributed across many nodes,
- a reference compiler that targets chunks while hiding the chunk model from the programmer, and
- a new model for sharing small “tasklets” among clients and servers in the cloud.

In most cases, while these contributions make use of our particular chunk abstraction, they can be adapted to traditional reference-based object systems and thus are useful independent of the Chunk Platform.

1.3.3 Thesis Outline

The next chapter details the Chunk Model. Chapter 3 outlines the Chunk Platform at a high level. A lower-level description of the Chunk Platform, including details of its application-generic run-time services, consistency model, and garbage collection algorithm, follows in Chapter 4. Chapters 5 and 6 evaluate the Chunk Platform through building chunk-based applications and evaluating chunk-based optimization techniques, respectively. After evaluation, the thesis continues with a review of related work in Chapter 7 and concludes with future work in Chapter 8.

Chapter 2

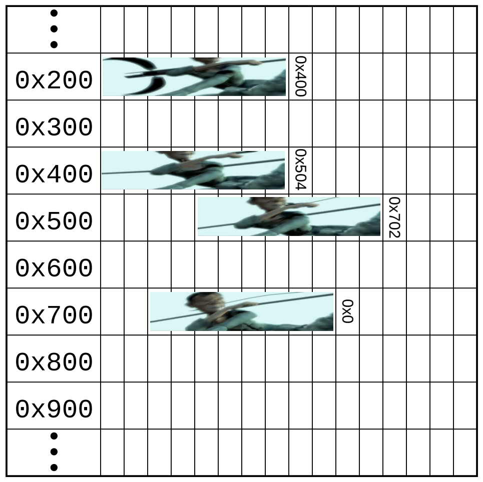
The Chunk Model

This thesis explores the Chunk Model as a more structured replacement for the unstructured memory abstraction of current computing models. The Chunk Model extends the standard von Neumann approach to computing with a structured memory rather than a flat memory. In doing so, the Chunk Model enables a structured way of storing everything, from data to computer programs to the run-time state of those programs.

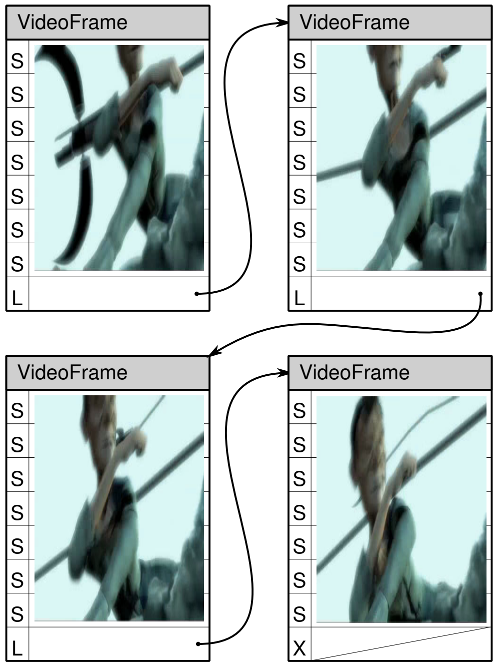
The Chunk Model differs from the current flat memory abstraction in three ways.

First, the Chunk Model replaces memory as a flat array of bytes with an unbounded universe of chunks. Chunks are fixed-size, so large data structures must be represented as graphs of many inter-referencing chunks. These graphs embody the Structural Transparency Principle and enable the Chunk Model to capture application-specific structure in a generic way.

Second, the Chunk Model replaces pointer arithmetic as a way of navigating memory with de-referencing explicitly-typed links between chunks. Chunks in the Chunk Model have identities, not addresses; the only notion of distance between chunks stems from the links between them rather than the nearness of addresses. Explicit links serve our transparency goal, since it allows run-time services to read graphs of chunks without complex analysis to disambiguate integers from pointers, while requiring chunk identities force the use of links to identify chunks, since there is no way to obtain a chunk except by de-referencing a chunk identifier. As Figure 2.1 illustrates with the last four frames of a video, rather than placing arbitrary data as a monolithic binary in the flat memory address space, the Chunk Model compels applications to place their data in a graph of chunks. At



(a) Flat Memory Model



(b) Chunk Model

Figure 2.1: A comparison of traditional flat-memory model and the Chunk Model using a video stream as an example. In the flat model, video frames are copied into the flat memory and connected by addresses at the end of frames. In the Chunk Model, individual frames are placed in chunks that are connected by explicit links.

run-time, rather than following pointers to specific addresses or computing addresses using pointer arithmetic, applications follow links inside chunks to other chunks. For example, in the figure, while an application in the flat model uses the integer addresses at the end of each frame to find the next frame, an application in the Chunk Model follows explicitly marked links.

Third, the Chunk Model replaces on-demand paging of memory with explicit placement of chunks in the memory hierarchy of a computing substrate. Just as current computers can address much more memory than they may physically possess, any given chunk-based computer is only able to reference a finite subset of the universe of chunks. Explicit placement of chunks enables substrate-specific run-time systems to customize chunk placement to best fit hardware-imposed constraints. In the example of Figure 2.1, the machine would load chunks into memory as the application walks down the linked list of frames. Compared to a virtual address system where pages are loaded when accessed, a chunk-based machine may anticipate paths taken in the chunk graph as hints to load chunks before they are needed.

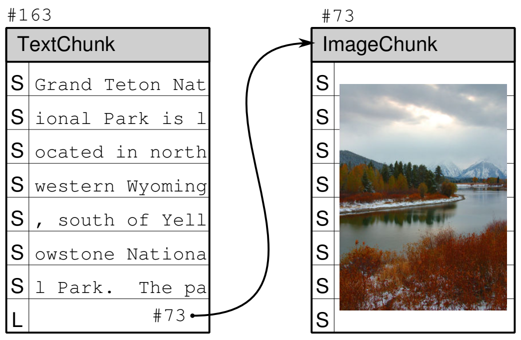


Figure 2.2: Two chunks with a link between them. The gray bar indicates the start of the chunk and contains the type hint. Each slot is typed with a type field (S for scalar and L for links).

2.1 Chunks

At the core of the Chunk Model is the chunk data type. A chunk is an ordered, fixed-sized array of fixed-sized slots. The number of slots in a chunk and the width of each slot is "universal" and shared by all nodes in the system.

Each slot consists of a type tag and a fixed-width data field. The type indicates how the data field should be interpreted: as an empty slot (X), as scalar binary data (S) or as a reference ("link", L) to another chunk. Scalar values are uninterpreted byte arrays; applications may store any scalar value they wish in a slot as long as that scalar value fits in the size limits of the slot. Chunk links are used to create large data structures out of graphs of chunks. Explicit typing of slots helps chunks achieve our goal of transparency since run-time analysis of the chunk graph need only look at the slot types to determine what are links and what are scalars. Chunk links are simply slots explicitly typed as references and filled with the identifier (chunk ID) of the referent chunk. Chunk IDs are opaque, network-neutral reference to chunks that are mapped to hardware locations at run time. Maintaining a level of indirection between chunk references and hardware enables platform-generic placement and migration of chunks.

Each chunk is annotated with a chunk type. The chunk type is a slot that serves as a specification of the semantics of the slots of the chunk. Applications and libraries use the chunk type as a hint on how to interpret the chunk's slots or for run-time data type checks.

Figure 2.2 illustrates two chunks with $N = 8$ slots. The chunk on the left is a TextChunk, which has the specification that the first $N - 1$ slots are scalar UTF-8 encoded text and that

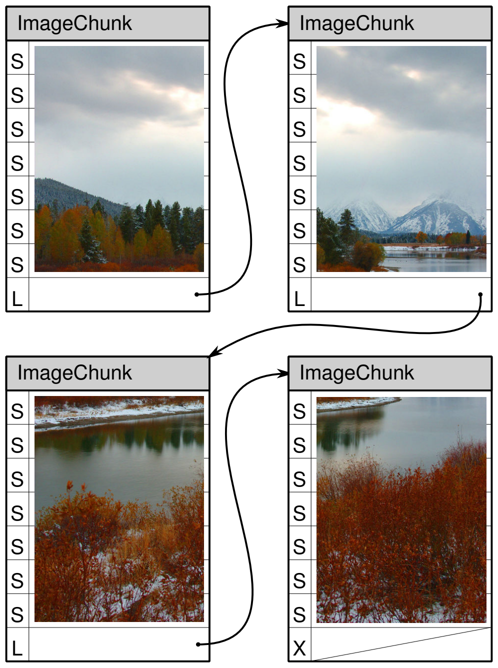


Figure 2.3: A large image spills over into multiple chunks.

the last slot is a link to a related chunk. The TextChunk links to an ImageChunk, whose specification states that the first $N - 1$ slots are packed binary data of a photograph, and that the last slot is either scalar data or a link to another ImageChunk if the encoding of the photograph does not fit in a single chunk.

Chunks may also be used as unstructured byte arrays by simply filling slots with uninterpreted binary data. For example, as shown in Figure 2.3, a larger version of the photograph in Figure 2.2 may be split across a linked list of four ImageChunk chunks.

2.2 Why Chunks?

This thesis uses chunks as its foundation data type for three reasons—generic structuring primitives, opaque identities, and fixed-sizes—each detailed in the subsequent paragraphs.

2.2.1 Transparent and Generic Structure

The first reason why we use chunks is that chunks embody a flexible, reference-based interface that can be used to build, link together, and optimize larger data structures one block at a time. Chunks can be used to implement any pointer-based data structure, subject to the constraint that the largest single element fits in a single chunk. Small chunks force the use of fine-grained data structures, creating many more decision, and optimization, points over whether or not to fetch a particular portion of a data structure.

Since the chunk interface is fixed and chunk links are network-neutral references, chunk-based data structures can be shared between any two nodes that use chunks without worrying about format mismatches. The chunk abstraction and the chunk interface is the embodiment of the Structural Transparency Principle of this thesis because chunks expose structure through the graph induced by the explicitly marked links. System-level code—like that handling coherence, caching, and optimization—can operate at and optimize the layers underneath the application using only the structure exposed by chunks without needing to worry about the exact semantics of each slot's value.

2.2.2 Identities Instead of Addresses

The second reason for using chunks is that chunk IDs are opaque references and not addresses. Opaque chunk IDs serve to break the abstraction of the flat virtual memory address space as well as provide a level of indirection between chunks and the locations where they are stored. The former is important because it removes the assumption that virtual addresses near each other have anything to do with each other, a fallacy because the contents of one virtual address may be in a L1 cache and available in a cycle while the next word in the virtual memory may be on disk and take millions of cycles to fetch. Breaking up a data structure into chunks makes it explicit that crossing a chunk boundary may impose a performance hit. Moreover, address arithmetic no longer works, meaning that data structures can only be accessed via paths in the chunk graph, rather than randomly. Doing so exposes the true cost of data structures, since (1) it is necessary to build helper chunks to access large data structures and (2) those data structures reflect, in chunk loads, the costs of accessing random items in memory normally obscured by the virtual memory subsystem.

The indirection property of opaque chunk IDs is important for two architectural reasons. First, it enables chunks to be moved around not only between processes, but also between nodes in the same network, giving a chunk-based run-time system the flexibility to not only place chunks within the memory hierarchy of one node, but also to place chunks on other nodes in the computation substrate. Second, using opaque chunk IDs frees the Chunk

Model from the inherent finiteness of an address-based namespace. While an individual node may be limited in the number of chunks it may hold due to the size of its own memory, there is no inherent limit on the number of chunks in the Chunk Model's universe of chunks: clever management and reuse of local chunk IDs by an implementation of the Chunk Model can provide an finite sliding window on the infinite universe of chunks.

2.2.3 Fixed Sizes

The third reason for using chunks is that since chunks comprise of a fixed number of fixed-sized slots, there is a limit to the total amount of information that a single chunk can hold as well as a limit to the number of chunks to which a single chunk can directly link. While fixed sizes may be seen as a limitation, size limits do have certain benefits. In particular, fixed-sized chunks, when combined with the reference properties of chunks, give rise to three useful geometric notions that aid run-time understanding of chunk data structures.

First, since building large data structures requires building graphs of chunks, the Chunk Model has an inherent notion of size. At the software level, size measures the number of chunks that comprise the entire data structure. At the hardware level, size measures the number of chunks that fit within a particular hardware unit. Knowing the relative sizes of data structures and hardware provides chunk-based systems with information to inform chunk placement algorithms. Small data structures are those that fit within the constraints of a hardware unit; large data structures are those that overflow a particular hardware unit and whose placement must be actively managed.

Second, chunks give rise to dual concepts of distance. At the data structure level, distance is the number of links between any two chunks in a data structure. At the run-time level, distance is the number of links followed during a particular computation. In an efficient data structure, related data are on chunks a small distance away from each other. Distance, in other words, leads to the notion of a local neighborhood of related chunks, both for passive data structures as well as for chunks needed for a given computation. Chunk-based systems may use distance information to infer which chunks should be placed together.

Lastly, chunks embody structure as a way of constraining the relationship between size and distance. Particular design choices may lead to differently-shaped data structures. Each of the different shapes may be useful for different problem domains. For example, the large

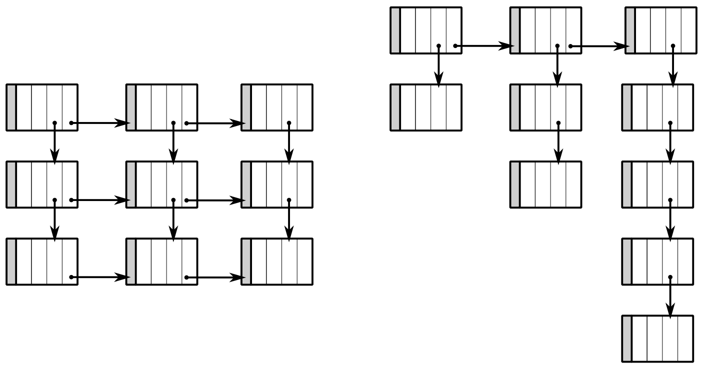

(a) 2-D Array (b) Progressive

Figure 2.4: Alternative chunk structures for storing image data.

image in Figure 2.3 is represented as a linked list of chunks, a long data structure that is appropriate if the image data can only be accessed as a single unit. If the image codec has internal structure, other choices may be better. For example, if the image is constructed as a two-dimensional array of image blocks, a 2-D array of chunks may be appropriate. If the image is encoded using a progressive codec where the more data that one reads the sharper the image gets, then a more appropriate chunk structure may be one that exposes more chunks as an application digs deeper into the data structure. As shown in Figure 2.4, the particular choices each beget a different shape, which may be used to more efficiently discover how the chunks will be used and inform how those chunks should be placed within the computing hardware.

2.2.4 Chunk Parameters

While the chunk abstraction requires the number of slots and the length of each slot to be fixed, this thesis does not advocate any particular binding of those parameters. Each computing substrate may require its own particular set of ideal chunk sizes:

- when running on top of a typical computer, chunks that fit within 4KB pages may be ideal;
- a computation distributed across a network may require chunks fit within 1,500 byte or 9,000 byte Ethernet frames in order to avoid packet fragmentation; while

- a massively multi-core machine may work best when a chunk fits in a small number of chip-network flits.

All that matters for the abstraction to work is that a particular choice is made, that the choice enable each chunk to have at least a small number of slots[1] and that the same choice is used throughout the computing substrate.

2.3 Example Chunk Structures

The Chunk Model enables the construction of application-specific data structures using a generic foundation; the only problem is figuring out how to represent application-specific data in chunks in a way that adheres to the Structural Navigability Principle. To help ground how chunks may be used consider two disparate problems: video streaming and general computing.

2.3.1 ChunkStream: Chunks for Video

Video is an ideal candidate for structured computing systems since video data is inherently structured, yet must be flattened into byte-oriented container formats for storage and transfer in traditional computing systems. Video container formats serve as application-specific structuring mechanisms in that they enable a video player to search within the byte-oriented video file or stream and pick out the underlying video codec data that the player needs to decode and display the video. Each container format is optimized for a particular use case and, as such, may offer only certain features. Some, like MPEG-TS [1], only allow forward playback, while others like MPEG-PS [1], AVI [69], and MKV [67] also allow video players to seek to particular locations, while others, like the professional-level MXF container format [3] are optimized for frame-accurate video editing.

ChunkStream's video representation is guided by the observation that video playback consists of finding frame data in the order it needs to be decoded and displayed. If the representation of each video stream were a linked list of still frames, playback would be the act of running down the linked list.

[1]The lower bound of the number of chunks per slot is two, making chunks akin to LISP `cons` cells, but we find that a lower bound closer to 8 is much more useful since it gives applications more room to distinguish between slots for their own purposes.

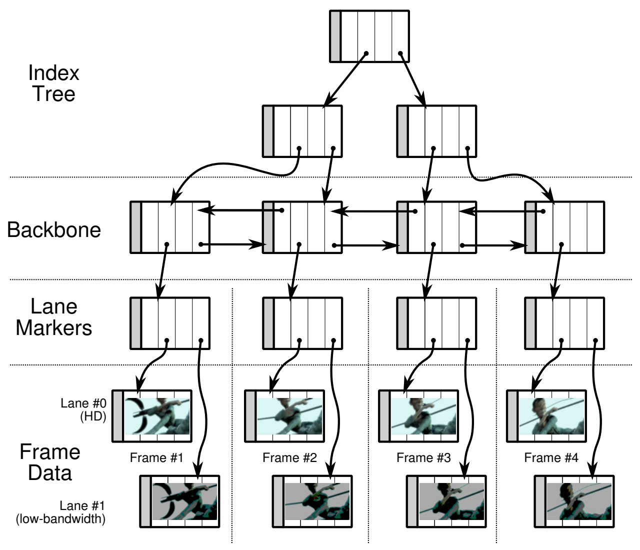


Figure 2.5: Chunk-based video stream representation used by ChunkStream. LaneMarker chunks represent logical frames and point to "lanes" composed of FrameData chunks. Each lane represents the frame in different formats, e.g. using HD or low-bandwidth encodings. Links to StreamDescription chunks and unused slots at the end of chunks are not shown.

With those observations in mind, ChunkStream represents video streams with four types of chunks, as illustrated in Figure 2.5. The underlying stream is represented as a doubly-linked list of "backbone" chunks that connect representations of individual frames. The backbone is doubly-linked to allow forwards and backwards movement within the stream. For each frame in the video clip, the backbone links to a "LaneMarker" chunk that represents the frame.

The LaneMarker chunk serves two purposes. First, it links to metadata about its frame, such as frame number or video time code. Second, the LaneMarker links to "lanes" of video. A lane is a video sub-stream of a certain bandwidth and quality, similar to segment variants in HTTP Live Streaming [81]. A typical LaneMarker might have three lanes: one high-quality high-definition (HD) lane for powerful devices, a low-quality lane suitable for playback over low-bandwidth connections on small devices, and a thumbnail lane that acts as a stand-in for frames in static situations, like a timeline. ChunkStream requires that each lane be semantically equivalent (even if the decoded pictures are different) so that the client may choose the lane it deems appropriate based on its resources.

Each lane takes up two slots in the LaneMarker chunk. One of these lane slots contains a link to a StreamDescription chunk. The StreamDescription chunk contains a description

```
def play(tree_root, frame_num):

    # Search through the IndexTree:
    backbone = indextree_find_frame(tree_root, frame_num)

    while playing:
        # Dereference links from the backbone down to frame data:
        lm_chunk = get_lane_marker(backbone, frame_num)
        lane_num = choose_lane(lm_chunk)
        frame_data = read_lane(lm_chunk, lane_num)
        # Decode the data we have
        deocde_frame(frame_data)

        # Advance to next frame in backbone:
        (backbone, frame_num) = get_next(backbone, frame_num)
```

Listing 2.1: Client-side playback algorithm for ChunkStream.

of the lane, including the codec, stream profile information, picture size parameters, stream bit rate, and any additional flags that are needed to decode the lane. Lanes are not explicitly marked with identifiers like “HD” or “low-bandwidth”. Instead, clients derive this information from the parameters of the stream: a resource-constrained device may bypass a 1920x1080 “High Profile” stream in favor of a 480x270 “Baseline” profile stream while a well-connected desktop computer may make the opposite choice. As an optimization, ChunkStream makes use of the fact that in most video clips, the parameters of stream do not change over the life of the stream, allowing ChunkStream to use a single StreamDescription chunk for each lane and point to that single chunk from each LaneMarker.

The other slot of the lane points to a FrameData chunk that contains the underlying encoded video data densely packed into slots. If the frame data does not fit within a single chunk, the FrameData chunk may link to other FrameData chunks.

Finally, in order to enable efficient, $O(\log n)$ random frame seeking (where n is the total number of frames), the top of the ChunkStream data structure contains a search tree, consisting of IndexTree chunks, that maps playback frame numbers to backbone chunks.

Video Playback

Listing 2.1 shows the algorithm clients use to play a video clip in ChunkStream. A client first searches through the IndexTree for the backbone chunk containing the first frame to play. From the backbone chunk, the client follows a link to the LaneMarker for the first frame, downloads any necessary StreamDescription chunks, and examines their contents to determine which lane to play. Finally, the client de-references the link for its chosen lane to fetch the actual frame data and decodes the frame. To play the next frame, the client steps to the next element in the backbone and repeats the process of finding frame data from the backbone chunk.

Advantages of the Chunk Model

An advantage of exposing chunks directly to the client is that new behaviors can be implemented without changing the chunk format or the protocols for transferring chunks between the video player and the video server. For example, the basic playback algorithm of Listing 2.1 can be extended with additional features by simply altering the order and number of frames read from the backbone. In particular, a client can support reverse playback by stepping backwards through the backbone instead of forwards. Other operations, like high-speed playback in either direction may be implemented by skipping over frames in the backbone based on how fast playback should proceed.

It is also possible to implement new server-side behaviors, such as live streaming of real-time video. Doing so simply requires dynamically adding new frames to the backbone and lazily updating the IndexTree so that new clients can quickly seek to the end of the stream.

2.3.2 CVM: Computing with Chunks

While ChunkStream is an example of using chunks for data structures, chunks are also a useful foundation for computation. One way to use chunks for computation is to make use of the standard "stored program" computer trick and use chunks as the backing store for all state—including executable code, program data, and machine state. Figure 2.6 shows an example computation expressed in chunks for a computing system based on closures and environments[2]. We call this the CVM data structure, since it represents a chunk-based virtual machine.

At the root of the data structure is a Thread chunk. The Thread chunk contains all of the run-time information that the computation needs: a link to the current environment (stored in Environment chunks), a link to the currently running code (enclosed in a Closure chunk), a "program counter" indicating where the next instruction can be found (pointing to Code chunks), a link to the previous invocation frame (e.g., the previous function on

[2]CVM hews closely to the "environment model" of execution explored in SICP [49, pp. 236–251].

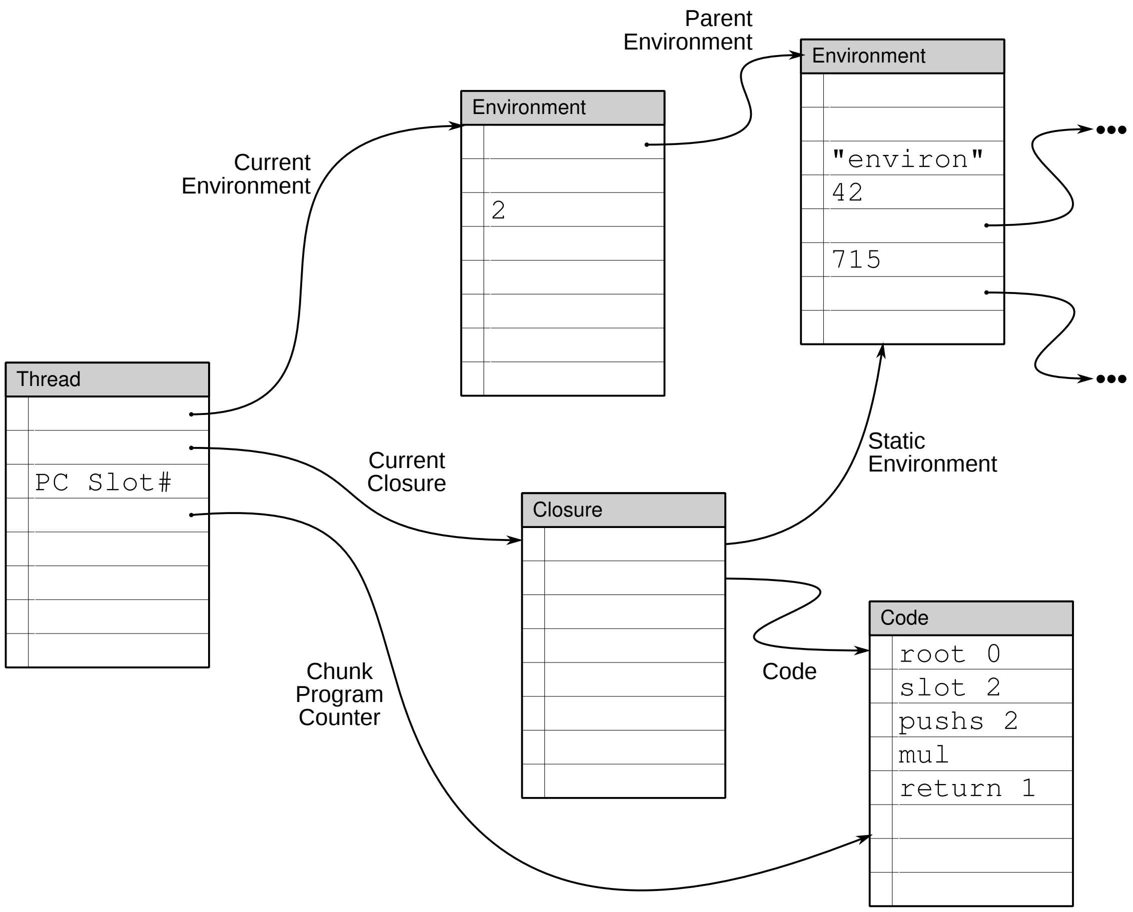


Figure 2.6: Illustrated snapshot of a CVM thread running double(n), for n=2.

the stack), as well as slots for temporary storage (e.g., machine registers or machine stack). Each Environment chunk represents a scoped environment for computations; each slot in the Environment chunks represents a program variable. The Closure chunk points to both the closure's static environment as well as its code.

A machine using the CVM data structure starts a cycle of computation by de-referencing program counter chunk and then reading the instruction at the program counter slot. The instruction may read or write temporary values in the Thread chunk or modify chunks linked to by the Thread chunk. After the instruction executes, the program counter is updated to point the next instruction, which may be in another chunk as in the case of branches or jumps.

Migration with CVM

A consequence of the Chunk Model only allowing chunks to reference other chunks through links is that CVM computations can only access chunks transitively linked from the root Thread chunk. This constraint forces the CVM data structures to be self-contained: each Thread chunk necessarily points to all of the code and data that the computation uses. A consequence of this property is that it is easy to move threads of computations between nodes running a CVM computation.

To migrate computation between CVM instances, the source VM need only send the root Thread chunk to the destination VM. As the destination VM reads links from the chunk, it will request more chunks from the source VM until it has copied enough chunks to make progress on the computation.

In many ways, the CVM migration strategy is similar to standard on-demand paging schemes. However, it is possible to exploit two properties of the CVM chunk representation to speed up migration. First, the fine-grained nature of the CVM data structure allows the migration of only small portions of running programs, such as an individual function, individual data objects, or even just the code and objects from a particular execution path, rather than an entire binary and its resident memory. Second, it is possible to exploit locality exposed by explicit links during the migration process and send all chunks within some link radius of the Thread chunk all at once, under the assumption that chunks close to a computation's Thread chunk are likely to be used by that computation. For example, in

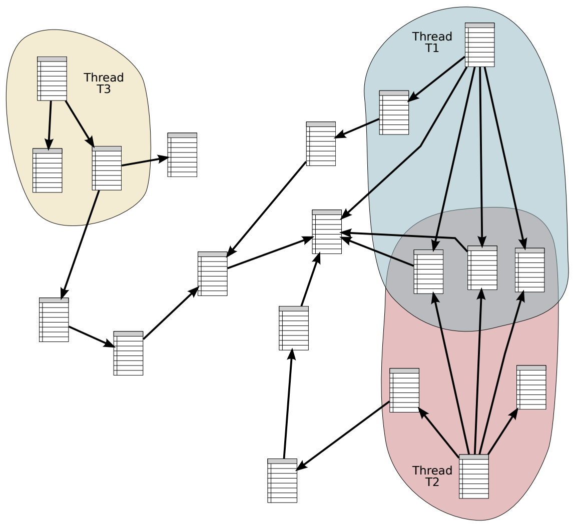


Figure 2.7: Three threads operating in a chunk space with their volumes of influence for $D_i = 1$ highlighted. Threads t_1 and t_2 are close to each other and must to be synchronized, while thread t_3 may run in parallel with the other threads.

Figure 2.6, the source might send the Thread chunk and the three chunks to which it links to the destination.

Volume of Influence

If one makes a few assumptions on the nature of CVM code, the fixed-size nature of chunks leads to interesting bounds on the mutations that a CVM computation can make. Suppose that CVM code consists of a sequence of instructions packed into Code chunks and each instruction can only access chunks some bounded distance D_i from the computation's Thread chunk. Each instruction may only bring a distant chunk closer by at most D_i links, i.e., by copying a chunk reference from a chunk a distance D_i away and placing it temporarily in the root Thread chunk. Since Code chunks, like all chunks, have a fixed size, there is a limit to number of instructions in each Code chunk and, correspondingly, a limit to how many chunks the instructions in the Code chunk can access before the computation must move on to another Code chunk. We call the limited set of chunks that the thread can access the *volume of influence* of the Thread. Suppose are N instructions in each chunk. If Thread chunks of two threads have roots that are $2ND_i$ apart from each other in the chunk graph, then they cannot influence each other during the execution of their current Code chunks. If two threads are closer than $2ND_i$, their volumes of influence may overlap and may need to be considered together by the hardware management and chunk placement layer.

For example, consider Figure 2.7, in which three threads execute in a chunk space. Threads t_1 and t_3 are far away from each other in the space and may be able to run concurrently without competing for resources like memory bandwidth. In contrast, threads t_1 and t_2 have overlapping volumes of influence and must time-share memory bandwidth and synchronize access to their shared chunks. The substrate's run-time system may be able to use this information to, e.g., place t_1 and t_2 on the same processor core so they can share chunks using higher-performance local communication primitives, while placing t_3 on a separate core that runs in near-isolation with no synchronization overhead with other threads.

Chapter 3

The Chunk Platform

The previous chapter outlined the Chunk Model, both as a data model and as a computation model. This chapter outlines the Chunk Platform, an implementation of the Chunk Model. The Chunk Platform serves as a vehicle for evaluating the hypothesis that preserving structure with chunks at machine abstraction layer makes it easier to provide system support for modern computing substrates.

There are many possible implementations of the Chunk Model, each of which makes different implementation choices emphasizing particular engineering trade-offs. Since our focus is on validating the Chunk Model, the design of the Chunk Platform is optimized toward experimenting with and debugging applications running on top of the model, and prototyping the systems layer that provides services like persistence, consistency, and garbage collection of chunks. The implementation of the Chunk Platform focuses on simplicity rather than raw performance. In doing so, the Chunk Platform provides a foundation focused on maximizing the abilities of the Chunk Model while minimizing the pain points, both in implementation and overheads, of using the Chunk Model.

3.1 Chunk Platform Overview

Recall that the Chunk Model targets modern computing substrates like general-purpose GPUs, massively multi-core processors, and elastic cloud computing systems. While modern computing substrates vary at the low level, they share two common properties:

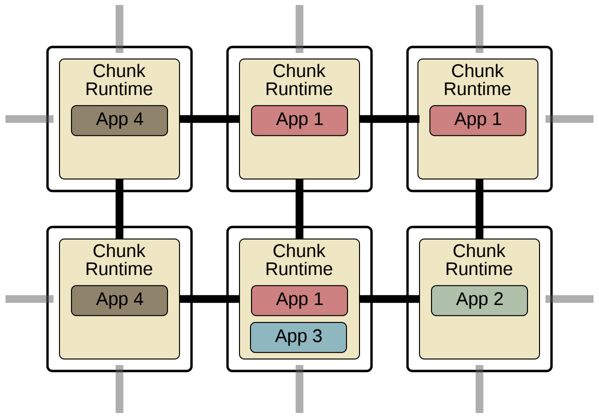


Figure 3.1: Overview of the Chunk Platform. Each substrate node runs a Chunk Runtime, which uses the substrate's local network connections to communicate with other Chunk Runtimes.

Local and Distributed Modern computing substrates are composed of independent components for which local interactions are far more efficient than long-range interactions. As these substrates scale in size and complexity, it becomes more difficult to build and maintain centralized global databases about the state of the system and its components.

Elastic Modern computing substrates are elastic and require balancing the use of extra computing elements with the costs, either in power or dollars, of using those elements. There are two parts to making an elastic computing system: expanding the amount of hardware a computation uses as the computation grows and shrinking the amount of hardware used as the computation finishes off.

The Chunk Platform embraces these common properties with two high-level design principles. First, the Chunk Platform shuns global routing and global shared memory and instead exploits local neighborhoods of connections between nodes to distribute the universe of chunks among the locally-available resources on each node. This design decision leads to a Chunk Platform architecture centered around a network protocol that leverages those local connections and resources to effect global changes in the universe of chunks. Second, since reclaiming resources in a distributed system can be complex and error-prone, yet is necessary to cost-effectively use modern computing substrates, the Chunk Platform provides distributed garbage collection to reclaim chunks as computations wane.

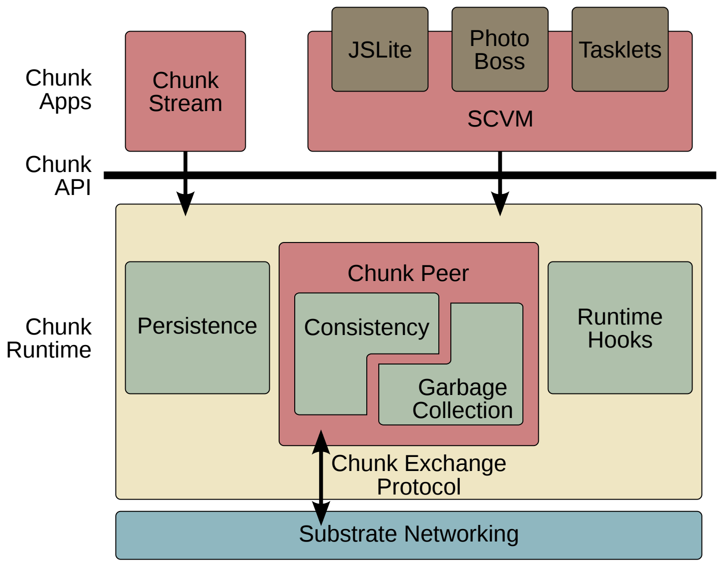


Figure 3.2: Architectural diagram of the Chunk Platform running on a single substrate node.

Figure 3.1 illustrates the overall architecture of the Chunk Platform as it fits into a generic modern computing substrate. Each node in the substrate hosts a Chunk Runtime, which, in turn, hosts one or more applications that use chunks. The Chunk Runtime on each node lets its applications create, read, and modify chunks distributed among the nodes. Chunk Runtimes communicate with each other using the Chunk Exchange Protocol. The Chunk Exchange Protocol manages where chunk copies are located, how copies are updated with modifications, and how allocated chunks are reclaimed when no applications need them anymore. Note that while the nodes and Chunk Runtimes in Figure 3.1 may look identical, the implementations of the Chunk Runtimes on each node may be different; the Chunk Platform only requires all Chunk Runtimes to use chunks of the same size and to communicate using compatible versions of the Chunk Exchange Protocol.

Figure 3.2 shows the software architecture of the Chunk Platform running on a single node. The Chunk Platform provides a Chunk API that serves as a concrete interface to the Chunk Model. Applications use the Chunk API to create, read, and modify chunks. In turn, the Chunk Runtime implements those API calls by using the Chunk Exchange Protocol to redistribute chunk copies so as to satisfy the contracts of the calls. In addition to the Chunk API, the Chunk Runtime provides generic system services for using chunks. These services include persistence of chunks, optimization libraries, as well as the Chunk Peer, which handles the Chunk Exchange Protocol. The Chunk Runtime is implemented on top of a substrate-specific networking layer, e.g., a layer using WebSockets [34] in the cloud, or on-chip networking instructions in massively multi-core processors.

The rest of this chapter details the particular choices for the Chunk API and the implementation of the Chunk Runtime that comprise the Chunk Platform.

3.2 The Chunk API and Memory Model

The Chunk API is the application-level expression of the Chunk Model: it provides a window into the shared universe of chunks and provides mechanisms for manipulating the chunk graph. The particular Chunk API we chose for the Chunk Runtime balances the needs of applications—providing standard mechanisms to create, modify, and find chunks—with the needs of the Chunk Platform—namely knowing when applications are actively using chunks or actively modifying chunks, in addition to determining when chunks are no longer needed by applications. As shown in Table 3.1, the API is divided into four groups of functions: functions to create chunks, functions to read chunks, functions to modify chunks, and system-level functions used internally within the Chunk Runtime to manage chunk references across the Chunk Platform's network of nodes.

3.2.1 API Usage

Chunks are created in two steps. First, applications call `new_chunk()` to create an nameless, ephemeral chunk. To insert the chunk into the Chunk Platform, the application calls `insert(chunk)`, which names the chunk with a chunk ID and persists it within local storage of the Chunk Runtime. Chunk IDs form the core linking abstraction for the Chunk Platform; once a chunk has been assigned an ID, that chunk can be used as a link target of other chunks as well as a parameter to the Chunk API. If an application attempts to de-reference an invalid chunk ID, the Chunk Runtime will raise an exception, much like de-referencing an invalid address may cause a virtual memory system to cause a general protection fault.

For example, to create the data structure in Figure 2.2, we first call `new_chunk()` to create the image chunk. After filling the chunk with image data, we call `insert()` to persist the chunk to the store; `insert()` returns an identifier (#73) to use to refer to the chunk. Next, we call `new_chunk()` a second time to create the text chunk. After filling the first seven slots with

Chunk Creation	
new_chunk() **returns** a chunk	Create a new, unnamed, uninitialized chunk.
insert(chunk) **returns** ID	Insert chunk into the store and return the chunk's identifier. The calling process will hold Modify privileges on the chunk.
Read API	
get(id) **returns** a chunk	Block until obtaining Read privileges on the chunk, then return the chunk.
wait(id, status) **returns** void	Block until the specified chunk has changed from the given status.
free(id) **returns** void	Release all privileges held for the chunk.
Modify API	
lock(id) **returns** a chunk	Block until obtaining Modify privileges on the chunk, then return the chunk.
modify(id, chunk) **returns** void	Modify the chunk associated with the chunk identifier so that it has the contents of chunk. Requires Modify privileges.
unlock(chunk_id) **returns** void	Downgrade Modify privileges to Read privileges.
Internal API	
bootstrap(id, from) **returns** void	Bootstrap reference to a chunk held on another node in the network.
gc_root_add(id) **returns** void	Add a chunk to the garbage collector's set of live chunks.
gc_root_remove(id) **returns** void	Remove a chunk to the garbage collector's set of live chunks.

Table 3.1: Chunk API exposed by the Chunk Runtime.

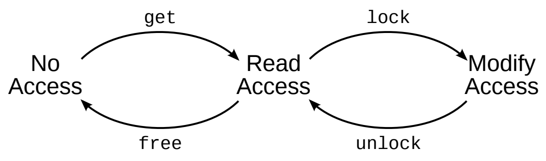


Figure 3.3: Access privileges of the Chunk API Memory Model

text data, we create the link in the eighth slot by filling the slot with the identifier of the target and marking the slot as a link. Finally, we call insert() to put the chunk into the store, which returns the chunk's identifier (#163).

After creating a chunk, applications use the other API calls to read and write chunks. Continuing the previous example, an application that knows the identifier of a chunk uses get() to retrieve the chunk. Using Figure 2.2 as an example, if a client has a local copy of chunk #163, then it may fetch chunk #73 by reading the contents of the last slot in chunk #163 and passing the slot's value to the get() call.

3.2.2 Memory Model

Each Chunk Runtime operates in concert with its neighboring Chunk Runtimes to determine how to distribute chunk copies so that applications that need to read chunks have copies to read and applications that need to modify chunks can do so coherently. The Chunk API provides a "privilege-based" memory model where an application must request and obtain a particular access privilege in order to access a copy of the chunk. Much like cache coherence protocols, the Chunk Platform uses the privilege requests to order chunk operations within the Chunk Exchange Protocol and uses the granting of those requests to control when applications may read and write chunks.

As illustrated in Figure 3.3, there are three levels of access:

No Access The application has no access to copies of the chunk.

Read Access The application may read, but not modify, a copy of the chunk.

Modify Access The application may read and modify a copy of the chunk.

The modify() API call requires that the Modify level be held. Applications that create new chunks start with Modify privileges for those new chunks. An application gives up its Modify access by calling unlock(), leaving the application with Read access. The get() needs

Read access in order to complete. The get() API call will block until Read level access is available, e.g., when no other local process or Chunk Peer has Modify access to the chunk. When an application is done using a copy of a chunk, it calls free() to give up all Read or Modify privileges on the chunk.

The Chunk API exposes a privilege-based memory abstraction since such an abstraction can be used to implement any memory consistency model depending on which operations block, which operations are asynchronous, and which operations are allowed to be rolled back [14]. The Chunk Runtime implements the Chunk API using a blocking, sequential consistency memory model [61]. We chose to implement a sequential consistency model because (1) programmers find sequential consistency, along with its close relative, processor consistency, the easiest memory models to program for and (2) sequential- and processor-consistent memory models still perform relatively well against harder to use relaxed memory models [6, 50].

3.3 Chunk Runtime

The Chunk Runtime provides an implementation of the Chunk API as well as a variety of system services useful to applications using chunks.

3.3.1 Persistence

One portion of the Chunk Runtime is the Chunk Store. The Chunk Store provides a backing store for chunks in use by the Chunk Runtime. The Chunk Runtime provides two implementations of the backing store. The first guarantees durability of chunks by storing them on a file system. The other trades off durability for speed by "storing" chunks in the local memory of the host. An individual node may choose which persistence layer to run when it boots its local Chunk Runtime.

3.3.2 Runtime Hooks

The Chunk Runtime provides hooks to profile applications using the Chunk API. The hooks provide a small API that allows an optimization plug-in to observe what chunks are requested by applications as well as what network and coherence events the applica-

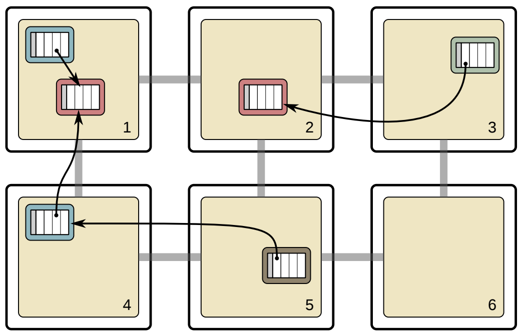


Figure 3.4: A simple data structure distributed over six Chunk Peers. Chunks filled with the same color represent copies of the same chunk.

tion's requests cause, hence allowing the optimization plug-in to develop a model of the application's use of chunks and potentially optimize access to chunks for the application.

3.3.3 Chunk Libraries

The Chunk Runtime also provides a set of libraries implementing common data structures like lists, trees, and maps as well as for packing and unpacking binary data. Applications use these libraries to adapt their internal uses of data structures to chunk-based data structures.

3.3.4 Chunk Peers and the Chunk Exchange Protocol

The Chunk Exchange Protocol part of the Chunk Runtime is responsible for managing communication with other Chunk Runtimes on other nodes in the substrate. The Chunk Exchange Protocol opens up the Chunk Runtime to requests and chunks available from other nodes in the computing substrate, enabling applications to span multiple nodes in the substrate as well as communicate through chunks to other independent applications. The Chunk Exchange Protocol enables the Chunk Runtime to extend the Chunk API from the limited collection of chunks available on a single node to the shared universe of chunks distributed among all of the nodes participating in the Chunk Exchange Protocol.

The goal of the Chunk Exchange Protocol is to provide a distributed shared memory with a simple consistency model and garbage collection. Garbage collection is important so that the Chunk Platform can meet its goal of elasticity by enabling computations to expand to other nodes in the system, but also contract as well.

The main functional requirements of the Chunk Exchange Protocol are that it provide ways to share chunks among nodes, find copies of a chunk for which a node only has a reference, and coherently modify chunks that may be distributed among many different nodes. For example, in Figure 3.4, a simple four-chunk data structure is distributed among six substrate nodes and Chunk Runtimes. Node 3 must be able to follow the link in the green chunk to find the red chunk on node 2. The Chunk Runtime must do the same for the brown and blue chunks. Likewise, if node 2 decides to modify the red chunk, the protocol must ensure that node 1, also holding a copy of the red chunk, is updated or invalidated.

These functional requirements come in the face of severe constraints the Chunk Exchange Protocol must adhere to. Recall that the Chunk Platform operates on computing substrates that do not guarantee global networking and globally shared memory. Instead, the Chunk Exchange Protocol must make use of locally available communication channels and memory. Such constraints are compounded by the fact that the Chunk Exchange Protocol must track each chunk individually, since the chunk is the atomic unit of the Chunk Model and the Chunk API. As such, the Chunk Platform must find ways to effect global change in the network using only small amounts of local state. To do so, the Chunk Platform makes use of a specialized data structure developed by Halstead [47] called a *Reference Tree*.

Within the Chunk Runtime, the Chunk Exchange Protocol is implemented by the Chunk Peer component. The rest of this chapter outlines the basic properties of Reference Trees and how they are useful for managing chunks using only local connections and state. The full implementations details of both the Chunk Exchange Protocol and the Chunk Peer that runs it follow in Chapter 4.

3.4 Reference Trees

Reference Trees are acyclic spanning trees that connect each node that holds a reference to or a copy of a particular chunk. There is a different Reference Tree for each chunk in the system. Figure 3.5 shows the distributed data structure of Figure 3.4 interposed with the Reference Trees for each of the four chunks in the diagram.

The Chunk Peer uses the Reference Tree to send Chunk Exchange Protocol messages to satisfy Read and Modify privilege requests from applications. Rather than use a global

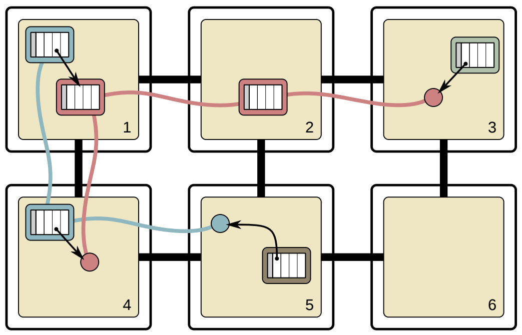


Figure 3.5: The Reference Tree for the data structure and applications of Figure 3.4. Rectangles with chunks show where Chunk Peers copies are in the Reference that have copies of the chunk, while circles indicate chunk references on Chunk Peers without a local copy of the chunk.

routing table and global networking, Reference Trees enable each Chunk Peer to send messages one hop at a time over the Reference Tree, based on completely local state.

At each node, the Chunk Runtime either holds a copy of the chunk, or uses a Reference Tree stub to find valid copies of the chunk. For example, in Figure 3.5, the link from the green chunk to the red chunk on node 3 points into the Reference Tree for the red chunk. If node 3 chooses to de-reference the green chunk's link, the Chunk Runtime at node 3 sends network messages along the Reference Tree until it finds a valid copy of the red chunk that can be sent back to node 3. The same pattern holds for the brown and blue chunks. The Reference Tree also keeps track of where each valid copy of a chunk exists, enabling a node that wishes to modify a chunk to contact other nodes with copies of the chunk to tell them to either invalidate their copies, or to update them with the changes.

3.4.1 Sequential Consistency through Invalidation

Once a Reference Tree is established, Chunk Runtimes send Chunk Exchange Protocol messages to each other to copy and move chunks among nodes in the Reference Tree. Recall that the single-node Chunk API of Section 3.2 provides a memory model-generic access-based API which the Chunk Runtime uses to provide sequential consistency. Similarly, the Chunk Exchange Protocol provides two generic consistency primitives—chunk copy requests and chunk evacuation requests—that are the foundation for building a distributed

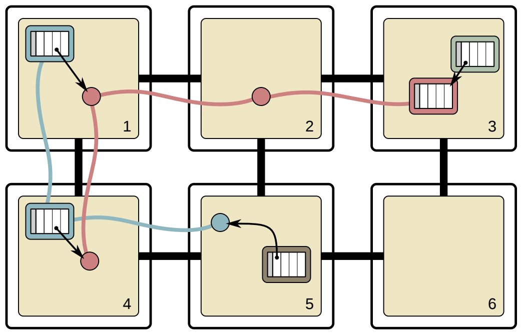


Figure 3.6: Reference Tree configuration that enables node 3 to grant a Modify privilege for the red chunk to a local application.

consistency model. The Chunk Exchange Protocol's messages and states are inspired by MESI-style [82] cache protocols.

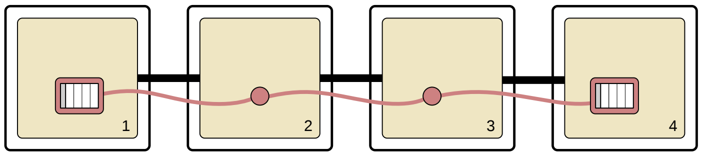
A node sends a chunk copy request, abbreviated C?, when it wants a copy of a chunk. When a node with a copy receives the C? message, it sends back a response with a copy of the chunk. A node sends a chunk evacuation request, abbreviated E?, towards a branch of the Reference Tree when it wishes for all copies available on that portion of the Reference Tree to be invalidated for consistency reasons. When an intermediate node receives an E? request, it recursively forwards the E? request to all downstream branches. Nodes that contain copies respond to the E? request by sending a copy of the chunk towards the requester while invalidating all local copies. Since the C? and E? requests are routed towards copies of chunks, the Reference Tree and its indications of where chunks are form a tiny routing table for the node, allowing the node to forward requests using only Reference Tree state.

The Chunk Platform implements distributed sequential consistency by using C? and E? messages to reconfigure which nodes in the Reference Tree hold copies of chunks. A Chunk Runtime running on a particular node will only grant Modify access to an application if that node holds the only valid copy of the chunk accessible over the Reference Tree. If there is more than one copy in the Reference Tree, then the Chunk Runtime attempts to shrink the number of copies to one. The Chunk Runtime does so by sending E? messages towards all branches of the Reference Tree that contain valid copies of the chunk and then blocking. When all of the of the branches have responded, the Chunk Runtime grants Modify access to the application. For example, if an application on node 3 of Figure 3.5 requests Modify access to the red chunk, the Chunk Peer on node 3 will send an E? message toward node 2 to evacuate copies of the chunk on that branch of the Reference Tree. Node 2 forwards the E? message to node 1. When node 1's applications relinquish their access privileges to the red chunk, node 1 responds to node 2 by giving up its copy of the chunk and sending it to node 2. Node 2, in turn, responds to node 3, by giving up its copy of the chunk and sending it to node 3. When node 3 gets a response from node 2, the Reference Tree for the red chunk will look as illustrated in Figure 3.6. At this point, node 3 knows that it has the only copy of the chunk and grants the Modify privilege to the application that requested it.

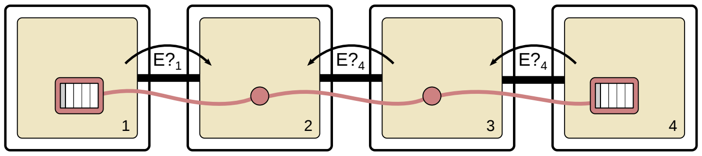
The Read privilege case is easier: the Chunk Runtime sends a C? message towards a branch of the Reference Tree that contains a copy and blocks until it receives a response. Since multiple nodes can have Read privileges to the same chunk at the same time, a node that receives the C? message can respond with a copy of the chunk as long as it hasn't granted Modify privileges to the chunk to a local application.

Since requests may be spontaneously generated by the Chunk Exchange layer in response to Chunk API calls from local applications, the Chunk Peer must take care to resolve race conditions so that competing, but conflicting requests, are not granted simultaneously. Rather than use a global clock or other time-based priority schemes, the Chunk Exchange Protocol orders requests by request type and then by the ID of the requester. Every Chunk Peer uses the same ordering so that each Chunk Peer responds to the same set of requests in the same order, even if they do not receive the requests in the same sequence.

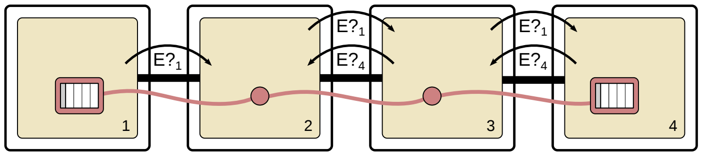
For example, in Figure 3.7, suppose that an application on node 1 and an application on node 4 both request Modify access to the same chunk. The E? request messages induced by those requests will necessarily cross each other as they flow through the Reference Tree towards copies that must be evacuated. When the requests intersect at node 2, node 2's node will order the messages based on priority. Since both are E? messages, the request from the node with the lower requester ID will win out and be serviced first. In the situation of Figure 3.7b, the $E?_1$ from node 1 will win out. When node 2 services node 1's higher priority E? request, node 2 will forward the higher-priority request towards node 3 since that branch of the Reference Tree contains a chunk copy that needs to be evacuated. At node 3, the $E?_1$ request becomes the new highest priority request, causing it to forward the $E?_1$ request towards node 4. When $E?_1$ reaches node 4, it will become the highest priority, beating out node 4's own request. As such, node 4 will respond by evacuating its copy of



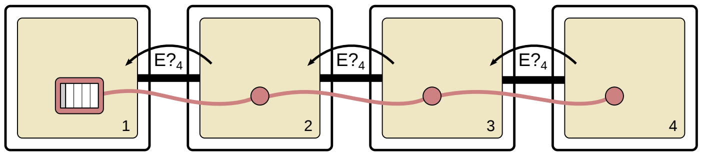
(a) Applications on nodes 1 and 4 request Modify privileges.



(b) The E? requests from nodes 1 and 4 reach node 2 simultaneously. Request E?$_1$ is higher priority, so node 2 will service it first by forwarding it towards the right.

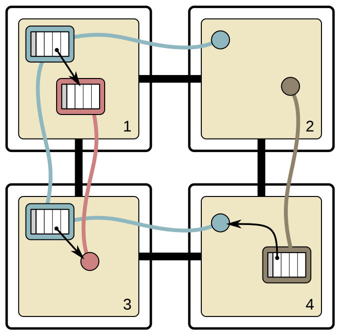


(c) Each node services E?$_1$ in preference to E?$_4$, including node 4, which gives up its copy of the chunk.

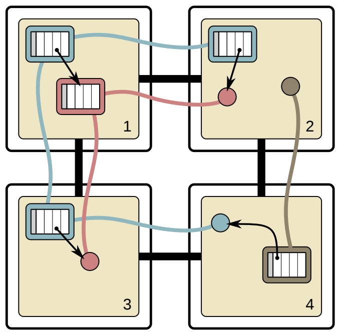


(d) E?$_4$ is eventually serviced when node 1's applications relinquish their privileges.

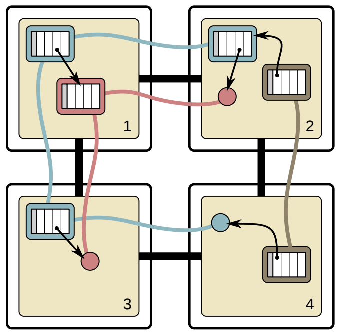
Figure 3.7: A race between two Modify privilege requests.



(a) Initial Reference Trees.



(b) Expansion of red Reference Tree by copying the blue chunk to node 2.



(c) Copying the brown chunk to node 2 reuses the existing Reference Tree for the blue chunk.

Figure 3.8: An example of Reference Tree expansion caused by copying a chunk between nodes.

the chunk, which will eventually let node 1 grant its application Modify access. Note that when node 1's application relinquishes its Modify access, node 4's $\mathsf{E?}_4$ request becomes the highest priority one, allowing the copy of the chunk to flow towards node 4 when node 1 is done with it, eventually enabling node 4 to grant its application the requested Modify privilege.

3.4.2 Reference Tree Expansion

The Reference Tree for a particular chunk expands when neighboring nodes learn about that chunk and need to connect to the Reference Tree in order to de-reference chunk links. Normally, this occurs when one chunk references another chunk and a copy of the first chunk moves to another node. When the copy moves, the Reference Tree for all of the chunks that the copy points to must expand to the new node where the copy is. If the Reference Trees did not expand, then the node receiving the chunk copy may run into errors when de-referencing the copy's links.

The Chunk Exchange Protocol uses a simple rule to expand the Reference Tree: if a Chunk Peer P_s sends another Chunk Peer P_d a chunk C, P_d can assume that P_s is a member of the Reference Tree for C's referents and use that to bootstrap its own Reference Trees. Figure 3.8 shows this in picture form. The blue chunk links to the red chunk. If node 2 requests a copy of the blue chunk from node 1, when node 1 sends the blue chunk to node 2, the Reference Tree for the red chunk must expand to node 2 so that node 2 knows how to de-reference all of the links in the chunk. The expansion results in the Reference Tree configuration of Figure 3.8b.

When the Reference Tree expands to encompass a new link, the Chunk Exchange Protocol must ensure that no loops are formed to maintain the acyclic property of Reference Trees. For example, in Figure 3.8, the Reference Tree for the blue chunk already extends to all of the nodes in the system. If the brown chunk were copied from node 4 to node 2, the Chunk Exchange Protocol prevents the link from node 4 to node 2 from being used in the blue chunk's Reference Tree. However, as shown in Figure 3.8c, rejecting the link will not break connectivity for the brown chunk's links, since node 2 is already is a part of the blue chunk's Reference Tree, allowing the system to find the chunk through the existing Reference Tree.

3.4.3 Garbage Collection

The previous section outlined how Reference Trees elastically expand as a computation or data structure grows to multiple nodes. However, expansion is only half of what is required for elastic systems—they must also contract to relinquish resources as computations wind down. The Chunk Platform relies on garbage collection to reclaim the resources allocated to chunks, using a strategy proposed by Halstead [47]:

1. The Chunk Runtime on each node runs a local garbage collector to determine which chunks are live for the applications running within that Chunk Runtime.

2. For each dead chunk, if the Chunk Peer has a local copy of the chunk, the Chunk Peer attempts to evacuate its copy to another node in the Reference Tree.

3. For each dead chunk, if the node is a leaf of the Reference Tree, the node attempts to leave the Reference Tree. A Chunk Peer may only leave the tree when it does not break the reference integrity of chunk links, so the attempt to leave the Reference Tree may fail. If the Chunk Peer successfully leaves the tree, it has the effect of shrinking the Reference Tree one node at a time towards the center of the Reference Tree.

4. If the Reference Tree for a chunk has shrunk to a single node, delete the chunk when that node no longer references it.

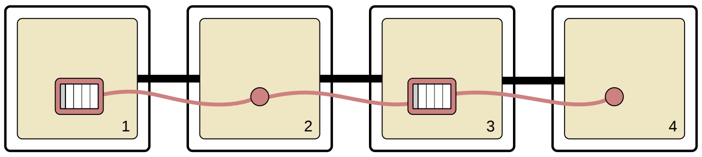
The above garbage collection strategy allows resources to be reclaimed incrementally: extra chunk copies are reclaimed through step 2, per-node Reference Tree metadata are reclaimed by step 3, and, finally, the last remnants of the chunk and its Reference Tree are reclaimed in step 4.

For example, consider the four nodes in Figure 3.9. Suppose that the local garbage collectors on all four nodes have determined that no applications make use of chunks; that is, the chunks are dead according to the garbage collector. According to the garbage collection strategy, only node 4 can leave the tree immediately. Nodes 2 and 3 must stay in the Reference Tree in order to maintain connectivity of the tree, while node 1 must stay in the Reference Tree until it evacuates its copy of the chunk.

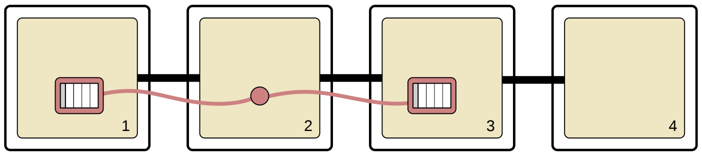
Suppose that node 4 leaves the Reference Tree. Figure 3.9b illustrates the resulting configuration of the Reference Tree. After node 4 leaves the Reference Tree, node 3 becomes eligible for leaving the Reference Tree if, like node 1, it can evacuate its copy of the chunk. Suppose that node 3 decides to leave the Reference Tree. To do so, it must evacuate its copy of the chunk. For reasons that will become clear later in this example, the Chunk Exchange Protocol disallows Chunk Peers from spontaneously sending chunks to another Chunk Peer. As such, node 3 cannot send its copy of the chunk to node 2. Instead, as shown in Figure 3.9c, node 3 must ask node 2 to *guarantee* the chunk, a process which induces node 2 to request a copy of the chunk from node 3. When the guarantee process completes and node 3 leaves the Reference Tree, the Reference Tree looks like Figure 3.9d.

At this point, nodes 1 and 2 are both leaves of the Reference Tree and can garbage collect the red chunk if they get rid of their copies. As alluded to before, nodes cannot spontaneously send copies to another chunk. This is because in a two node situation it is possible for the two nodes to send chunks to each other while believing that the other node no longer has a copy, breaking the Reference Tree. The guarantee process prevents this because guarantees are requests and like any other request in our system, they are prioritized and ordered. Therefore, if nodes 1 and 2 simultaneously send guarantees to each other, due to request ordering rules, node 1's guarantee request will win out and it will be able to leave the Reference Tree first. This situation is illustrated by Figure 3.9e.

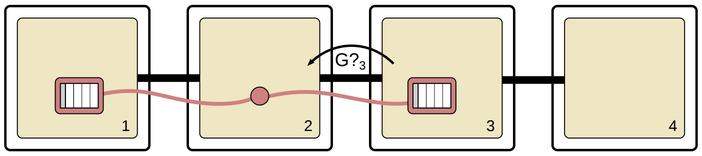
After node 1 leaves the Reference Tree, only node 2 knows about the chunk, as illustrated in Figure 3.9f. It can delete the chunk whenever it needs to, completing the process of garbage collecting the chunk and its Reference Tree.



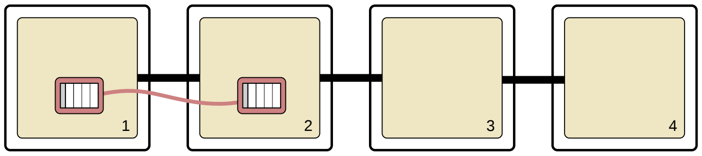
(a) Initial Reference Trees.



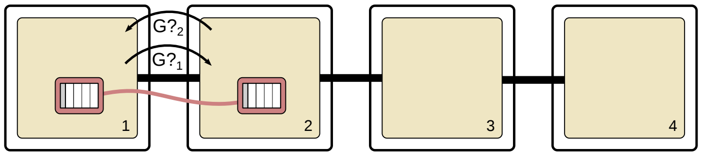
(b) Reference Trees after node 4 leaves.



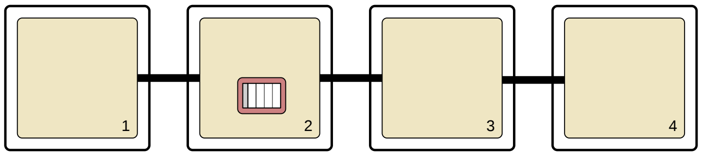
(c) Node 3 must ask for a guarantee to evacuate its copy of the chunk.



(d) Reference Trees after node 1 leaves.



(e) Guarantee requests enable the Chunk Peer to overcome race conditions during garbage collection.



(f) Reference Trees after node 2 leaves.

Figure 3.9: Garbage collection example.

Garbage collecting chunks essentially amounts to garbage collecting Reference Trees from nodes that no longer reference those Reference Tree's chunks. As the example shows, the key problem in garbage collecting Reference Trees is determining when a node can leave the Reference Tree without breaking the referential integrity of chunk links—for chunks referenced locally as well as for chunks referenced by other nodes. This is the subject of the next chapter.

Chapter 4

Taming the Chunk Exchange Protocol

Chapter 3 outlined the architecture of the Chunk Platform and how it uses Chunk Peers, the Chunk Exchange Protocol, and Reference Trees to share, update, and garbage collect chunks dispersed among multiple nodes in a computing substrate. This chapter details the implementation of the Chunk Peer, from the low-level network messages of the Chunk Exchange Protocol up to the high-level state maintenance loop that runs at the core of each Chunk Peer component of the Chunk Runtime.

4.1 Chunk Peer

The Chunk Peer component that implements the Chunk Exchange Protocol consists of two layers. At the lower level is the Channel layer, consisting of Channel Proxies connected to each networking channel in the computing substrate. At the higher level is the Chunk Exchange layer, consisting of several components that implement the decision making of the Chunk Exchange Protocol.

The Chunk Peer is implemented as two layers to enable separation of concerns and to make the Chunk Peer implementation more modular. The Channel layer manages substrate networking and maintains the Reference Trees. The Chunk Exchange layer assumes that the Channel layer provides a working Reference Tree and uses that Reference Tree to (1) handle the consistent and coherent distribution of chunk copies, (2) mediate requests between neighboring Chunk Peers and locally running applications, and (3) manage garbage collection of Reference Trees and chunks.

Both the Channel layer and the Chunk Exchange layer are implemented as finite state machine-like event processing loops that handle incoming events, update local state based on those events, and then issue responses to those events. Each Reference Tree, and consequently, each chunk, is tended to by independent instances of the Channel layer and Chunk Exchange layer components.

Each Channel Proxy in the Channel layer reacts to Chunk Exchange Protocol messages that come in from its channel. The Channel Proxy parses the network messages to determine whether the message is a request or a Reference Tree status update. If it is a status update, the Channel Proxy updates itself to reflect the new status of the branch of the Reference Tree available over that channel. If the network message is a request, the Channel Proxy forwards the request to the Chunk Exchange layer. After handling each incoming message, the Channel layer wakes up the Chunk Exchange layer so it can handle any updated state or requests.

The Chunk Exchange layer reacts to changes in state at the Channel layer as well as Chunk API calls from locally running applications. Every time it is woken up, the Chunk Exchange layer attempts to satisfy the highest-priority request it knows about. If it can satisfy the request, it does so and deletes the request so it can move on to the next one. Otherwise the Chunk Exchange layer sends additional requests through the Channel layer to other Chunk Peers, or if there is nothing more to do, the Chunk Exchange layer suspends itself until new requests or updates come in.

4.2 Distributed Reference Trees

While the previous chapter discussed Reference Trees as though they are globally consistent and centrally maintained data structures, in truth Reference Trees are decentralized data structures whose state is distributed over all Chunk Peers participating in each Reference Tree.

Each Chunk Peer keeps only enough state about each chunk's Reference Tree to route messages and respond to requests for that chunk. In particular, rather than storing, and needing to maintain, the exact form of each Reference Tree at each node, the Channel layer of the Chunk Peer instead maintains Channel States for each channel the Chunk Peer has for each chunk the Chunk Peer references. The Channel State for a channel summarizes

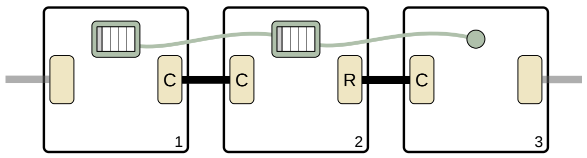


Figure 4.1: Illustration of a Reference Tree and how its state is distributed among its constituent Chunk Peers. The Channel Proxies of each channel hold the channel's Channel State. The black substrate channels are included in the Reference Tree while the gray ones are not.

the configuration of the Reference Tree branch available over that channel. The Channel State is stored in and maintained by the Channel Proxy attached to a particular channel. Figure 4.1 illustrates the Channel States for a particular Reference Tree. The three most essential Channel States are I, for a channel not involved in the Reference Tree; R, marking channels on the path to other nodes in the Reference Tree; and C, marking channels on the path towards a valid copy of the Reference Tree's chunk. For example, the Channel Proxy at the left of node 2 is in the C state, since a valid copy of the Reference Tree's chunk can be found on the other side of the channel at node 1. The right Channel Proxy of node 2 is in the R state since at least one node on the other side of the channel is in the Reference Tree, but there are no valid copies. The two Channel Proxies at the extreme left and right of the diagram are in the I state. They are not used because the Reference Tree only spans the three nodes in the diagram and those channels lead to nodes not involved with the Reference Tree.

The Chunk Peer's per-channel summarized representation of a Reference Tree is convenient for two reasons. First, since the Chunk Exchange Protocol C? and E? requests are routed towards copies of chunks, the Chunk Peer can route those requests simply by looking at the Channel State for each channel. For example, if node 2 in Figure 4.1 needs to service an E? request from the right-side branch of the Reference Tree, it forwards the request towards all channels in the C state (namely, towards node 1 on the left).

Second, the summary-based representation enables the Chunk Peer to handle dependencies for requests. Continuing the example above, node 2 in the center of Figure 4.1 cannot respond to the E? request until every branch of the Reference Tree downstream from the request has invalidated its copy of the chunk. When a branch of the Reference Tree has invalidated its copies of the chunk, the Channel State for that branch will eventually revert to the R state. As such, node 2 may respond to the E? request when all of the downstream channels are in the R or I state.

Note that the summary-based representation of Reference Trees relies heavily on the fact that Reference Trees are acyclic data structures. If loops were allowed, then the summary of a branch of the Reference Tree may include information about the node itself, muddying the true state of the Reference Tree.

If a channel is in the Reference Tree, at most one of the two Channel Proxies attached to that channel may be in the R state at any given time. To prove this requirement, assume that both sides of the channel are in the R state. This means that there is no path using the channel to a valid copy of the chunk. Given that Reference Trees guarantee that there's exactly one path between any Chunk Peer and a given copy of the chunk in the Reference Tree, if both channels were in the R state, then (1) there are either no copies anywhere in the Reference Tree network (a violation of the referential integrity of chunk links) or (2) there is a loop in the Reference Tree with no copies in it (violating the acyclic property of Reference Trees). Note that the Channel Proxies on each side of the channel may both be in the C state if there is a valid shared copy of the chunk available from both sides of the channel. The channel between nodes 1 and 2 in Figure 4.1 is in such a configuration.

4.3 Chunk Exchange Protocol Messages

Messages are the vocabulary of the Chunk Exchange Protocol since they define what state Chunk Peers expose to each other and what requests each Chunk Peer may make of its neighbors using that state information.

4.3.1 Message Structure and Nomenclature

Chunk Exchange Protocol messages consist of a message type, which defines the content of the message, a chunk ID, and a list of parameters, the semantics of which are defined by the message type. The chunk ID is needed to de-multiplex messages coming in over the shared network channel and send them to the Channel Proxy and Chunk Exchange instances managing that chunk's Reference Tree.

Request	Shortcut	Description
E?	Evacuate	Request exclusive access to a chunk
C?	Copy	Request a copy of the chunk
G?	Guarantee	Request Chunk Peer to guarantee the existence of the chunk
B?	Bootstrap	Request a bootstrap to the Reference Tree
(J?)	Join	Implicit request to join the Reference Tree

Table 4.1: Chunk Exchange Protocol Request messages, in order of decreasing priority (with the last three messages of equal priority). The (J?) message is the implicit join request implied by every link in a chunk received over a channel.

There are two classes of message types: requests and status messages. The requests are what make the Chunk Exchange Protocol tick; without them the Reference Tree would not grow, change, or shrink. Status messages are the responses to requests.

As shown in Table 4.1, there are five request message types. The names for request messages all end in ? indicating that the requests are essentially questions to be answered by the Reference Tree network. All request messages contain a priority parameter, which is used to resolve race conditions in request dissemination (as used in Section 3.4.1).

The B? and (J?) messages are used to expand the Reference Tree to other nodes. The B? message is used to manually bootstrap nodes in the Reference Tree and is relatively rare. Most Reference Tree expansion messages come in the form of the implicit invitation to the Reference Tree that comes with the movement of every chunk copy, as was demonstrated by Figure 3.8 in Section 3.4.2. We represent that implicit invitation with the implicit (J?) message. The (J?) message never actually appears over the wire; it is only useful as a construct to manage the Channel State FSM. The E? and C? requests are used to manage where copies of the chunk are in the Reference Tree once it is established. The G? request is used during garbage collection as part of the process of enabling a Chunk Peer to give up its copies of chunks, as was shown in Figure 3.9c in Section 3.4.3.

Status messages convey the status of the Reference Tree as available from the node sending the status message. A + suffix indicates that there is a chunk copy available on the channel from which the message arrived, while a – suffix indicates that there are no copies available from that channel—the Chunk Peers available through that channel only have references to the chunk. Lastly, a U suffix means that the channel cannot be, or should no longer be, used in the Reference Tree. The U-suffixed messages are used as responses

Message	Description
R+	Channel used in Reference Tree; chunk copy available from this channel
R-	Channel used in Reference Tree; no copies available from this channel
RU	Channel not in Reference Tree
C+	Copies available from this link; copy of chunk in message
C-	No copies available from this link; copy of chunk in message
CU	Channel not in Reference Tree; copy of chunk in Message

Table 4.2: Chunk Exchange Protocol status messages.

to Reference Tree expansion requests that cause loops and during garbage collection to remove branches from Reference Trees.

Sending a status message across a channel affects both sides of the channel and may lead a channel to change its state and, consequently, the configuration of the Reference Tree. The particular status messages we use are designed to directly correlate with the Channel State summaries each Chunk Peer maintains. There are two classes of status messages: Reference Tree management messages and chunk copy management messages, both shown in Table 4.2. Reference Tree messages (R+, R-, and RU) are used to manage membership of the Reference Tree. They are only used in response to B? and (J?) requests to establish the Reference Tree and during garbage collection. Copy management messages (C+, C-, and CU) contain serialized copies of chunks in their body and are used to move valid copies of chunks among the nodes of the Reference Tree once the Reference Tree is established.

4.4 Channel Layer and Channel Proxies

The Channel Proxies (1) bootstrap new nodes into the Reference Tree and (2) update Channel States of established Reference Trees as copies migrate between nodes of the tree.

The Channel Proxies summarize the state of the Reference Tree using one of the six Channel States shown in Table 4.3. Of the states, four (I, N, R, and C) are stable states that the Channel Proxy will settle on in a Reference Tree whose membership is not changing. The N state is used for channels that would cause a loop in the Reference Tree. While not strictly necessary since the Chunk Exchange Protocol will discover and prevent loops when Reference Trees expand, remembering which channels cause loops reduces the number

State	Name	RT?	Copies?	Notes
I	Invalid	N	N	Channel not in Reference Tree.
N	Not Used	N	N	Channel would cause a loop.
R	Reference	Y	N	
C	Copy	Y	Y	
U	Unknown	?	?	Transient state between I and the stable states.
G	Guaranteeing	Y	Y	Transient state when remote Chunk Peer leaves Reference Tree.

Table 4.3: The Channel States of the Chunk Exchange Protocol. The “RT?” column indicates whether or not the channel is in the Reference Tree while the “Copies?” column indicates that at least one valid copy of the chunk may be found via that channel. The first four states are stable states of a stable Reference Tree, while the U and G states are transient states that occur while, respectively, growing and shrinking the Reference Tree.

of messages that the Chunk Peer must send when expanding Reference Trees. The two remaining states, U and G, are transient states used when the Reference Tree is expanding and contracting, respectively.

The Channel Proxy maintains the Channel State using two techniques. To extend a Reference Tree to new nodes, the Channel Proxy uses four bootstrap procedures that initialize the Channel State. Once a channel is in the Reference Tree, the Channel Proxy uses a small finite state machine to update the Channel State as status messages are sent or received over its channel.

4.4.1 Extending the Reference Tree

When a chunk is first created, each substrate channel starts in the I state because the node that created the chunk is the only one that knows about the chunk and, accordingly, the Reference Tree for the chunk does not extend beyond that one node. A channel leaves the I state when the Reference Tree is extended to include the channel and the node on the other side of the channel. The key challenges in extending the Reference Tree are (1) determining whether the new channel causes a loop in the Reference Tree and (2) initializing the Channel State variables properly.

There are two ways to extend the Reference Tree to another channel. As outlined in Section 3.4.2, the typical way is to have a copy of a chunk drag the Reference Trees of its referents to new nodes. When a copy of a chunk passes through the Channel Proxy, the Channel Proxy runs one of the handlers in Listing 4.1 to initialize the Channel State. The

```
def on_send_chunk(chunk):
    for slot in chunk.slots:
        if slot.type == LINK:
            channel_state = get_channel_state(slot.chunk_id)
            if channel_state == I:
                set_channel_state(slot.chunk_id, U)
            else:
                # Already in Reference Tree, no need to change
                continue

def on_receive_chunk(chunk):
    for slot in chunk.slots:
        if slot.type == LINK:
            channel_state = get_channel_state(slot.chunk_id)
            if channel_state == I:
                # Channel not in the Reference Tree. We need to
                # figure out if the channel causes a loop in the
                # Reference Tree.
                if already_in_rt(slot.chunk_id):
                    # We're already in the Reference Tree; adding this
                    # channel would cause a loop. Tell our network
                    # peer not to use the link ...
                    send_message("RU", slot.chunk_id)
                    # ... and don't use it ourselves:
                    set_channel_state(slot.chunk_id, N)
                else:
                    # We're not in the Reference Tree. Tell our
                    # network peer to use the link by telling it we
                    # don't have any copies of the chunk this way)...
                    send_message("R-", slot.chunk_id)
                    # ... and set up the link so that we know where to
                    # find copies of the chunk
                    set_channel_state(slot.chunk_id, C)
            else:
                # Channel state already agreed upon, so no need to
                # change.
                continue
```

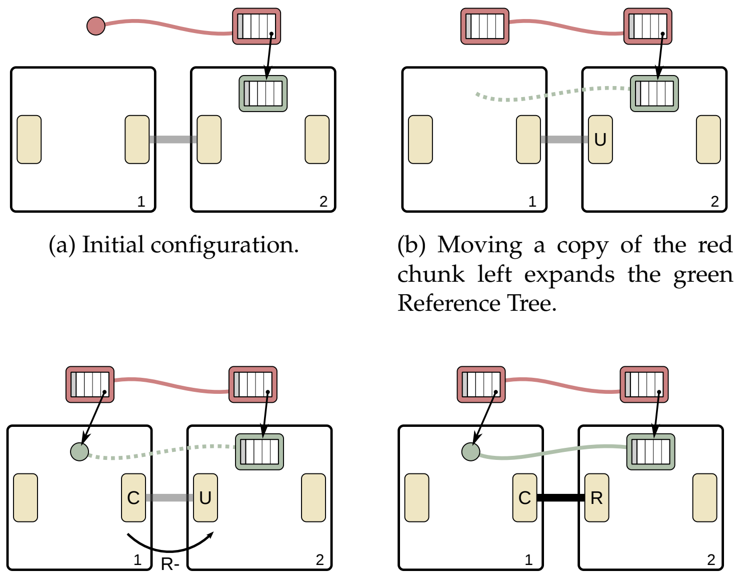
Listing 4.1: Channel Proxy state handling procedures used to extend the Reference Tree using (J?) messages.

```
def on_send_bootstrap(chunk_id):
    channel_state = get_channel_state(chunk_id)
    assert channel_state == I, "Error: attempt to bootstrap in-use channel"
    set_channel_state(chunk_id, U)

def on_receive_bootstrap(chunk_id):
    channel_state = get_channel_state(chunk_id)
    assert channel_state == I, "Error: attempt to bootstrap in-use channel"

    # Tell bootstrapper that it can use the link to find chunks this
    # way
    send_message("R+", chunk_id)
```

Listing 4.2: Channel Proxy state handling procedures used to extend the Reference Tree using explicit B? messages.



(a) Initial configuration.

(b) Moving a copy of the red chunk left expands the green Reference Tree.

(c) The left node responds that it can join the Reference Tree with an R- message.

(d) The expanded Reference Tree.

Figure 4.2: Chunk State as a copy moves to another node.

other way is with an explicit bootstrap B? message, which causes the Channel Proxy to run one of the handlers in Listing 4.2. In both sets of handlers, the sending side puts itself in the transient U state and then waits for a status message from its neighboring peer. The receiving side is responsible for figuring out whether or not the link can be added to the Reference Tree. If it can, then the receiving side responds with an R+ or R- message, which is handled through the normal state update procedure outlined in the next section. If the link would cause a loop, the receiving side responds with an RU message, which prevents both sides from using the channel.

For example, as shown in Figure 4.2, the right node transfers a copy of the red chunk to the left node. This causes the Reference Tree of the green node to expand to the left node. In the first stage of the expansion, the right node sets its Channel State to U. In this case, the left node is not a member of the Reference Tree yet, so it links its copy of the red node into the green Reference Tree. The left node then responds with an R- message indicating it wishes to join the Reference Tree. When the right node receives the R- message, it finalizes the state according to the Channel State FSM (described below), resulting in Figure 4.2d.

		Send			Receive			Send			Receive		
Current State		R-	R+	RU	R-	R+	RU	C-	C+	CU	C-	C+	CU
I	(Invalid)						I						I
U	(Unknown)				R	C	N						
N	(Not Used)			I			I						
R	(Reference)			I			I	C	C	I			
C	(Copy)			I				C	C	I	C	R	I
G	(Guaranteeing)							G				R	I

Table 4.4: Transition table of the Channel Proxy FSM. Blank cells indicate an error condition.

4.4.2 Reference Tree Status Maintenance

The Channel Proxy updates its Channel State as status messages are sent or received according to the transitions in Table 4.4.

The bootstrap functions of the last section leave the sending Channel Proxy in the U state waiting for R messages to take it to a stable Channel State. The R message transitions take care of resolving the U state. If the remote Chunk Peer rejects the channel by responding with a RU message, then the state of the channel moves to N, indicating that the Chunk Peer on the other side of the channel is in the Reference Tree, but that using the channel would cause a cycle in the Reference Tree, violating the acyclic property of Reference Trees. If the remote Chunk Peer joins the Reference Tree by responding with a R+ or R- message, the state of the channel moves to C or R, respectively. Once the channel has left the U state, the Channel Proxies will both be in the compatible states, either both in the N state or one in the R and one in the C state.

Once a channel is established in the Reference Tree, the channel's Channel Proxies move between the R and C states as C+ and C- messages flow through the channel in response to C? and E? requests. Note that the transitions in Table 4.4 combined with the fact that C+ and C- messages that move chunks within the Reference Tree ensure that at most one side of a channel is in the R state at any given time, even during transitions. Suppose that Chunk Peer P_s transfers a chunk to Chunk Peer P_d using a C- message. Since P_s has a copy of a chunk to send, P_d's Channel Proxy for the shared channel must be in the C state. Assuming that the substrate network is reliable, when P_s sends the C- message, it immediately invalidates its own copy and sets the Channel State for P_d to C, since it knows that when P_d receives the C- message it *must* have a copy of the chunk (namely, the copy in the message). When P_d processes the C- message, it sets the sending P_s's Channel State to R. At no time are both sides of the channel in the R state.

The RU and CU messages cause both sides of the channel to revert back to the I state. While N channels are ignored in most Reference Tree actions (since they are not part of the Reference Tree), they need to be included when a peer leaves the Reference Tree so that the other end of the channel knows it is possible to re-use the channel in the future if the Reference Tree expands again. As such, when a node leaves the Reference Tree, it broadcasts an RU message across all of the N channels to reset their state back to the I state, completely resetting the Channel State to its initial invalid state.

4.5 Chunk Exchange Layer

The Chunk Exchange layer sits between the network-level Channel layer and the application-level Chunk API and manages the consistency and garbage collection of chunks. The Chunk Exchange layer consists of several major components. The first component is an ordered queue of requests called the Request Queue. The Request Queue orders and mediates requests from the Channel layer and the Chunk API layer. The second major component is the Chunk State component, which keeps track of the local disposition of the chunk. The third major component is the Garbage Collector, which determines which chunks are in use by applications in the Chunk Runtime. The last major component, the Reactor, is also the most important, since it governs how the Chunk Peer reacts to changes in the Reference Tree, the Request Queue, the Garbage Collector, and the Chunk State of the chunk.

Figure 4.3 illustrates the components and how they connect to each other. The Request Queue takes in requests from the Channel layer, the Chunk API layer, and the Garbage Collector, since they are the three sources of chunk-level requests. The Chunk State component is connected to the Chunk API layer, the Chunk Store, the Garbage Collector, and the Reactor, since those components affect the chunk's state.

The Reactor sits at the middle of all of the components. The goal of the Reactor is to process the Request Queue while maintaining the invariants of the Reference Tree and the sequential consistency model. It takes as input the Reference Tree state from the Channel layer, the top-most request from the Request Queue, and the local state of the chunk from the Chunk State component. The Reactor produces as output messages to be sent by the

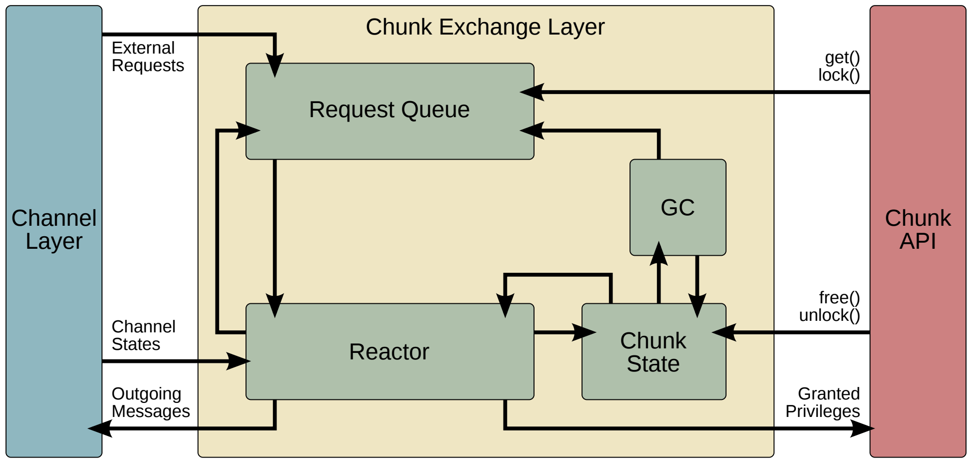


Figure 4.3: The components of the Chunk Exchange layer.

Request	Type	Priority	Description
Modify	Local	1	Request for Chunk API Modify privilege
E?	Tree	1	E? Request from other Chunk Peer
Read	Local	2	Request for Chunk API Read privilege
C?	Tree	2	C? Request from other Chunk Peer
G?	Tree	3	G? Request from other Chunk Peer
Leave	Local	4	Request from Garbage Collector to leave Reference Tree

Table 4.5: The six types of requests of the Chunk Exchange layer, grouped by priority. Requests with priority 1 are the highest priority requests.

Channel layer, API responses to be sent to the Chunk API layer, and modifications to the local Chunk State. The Reactor executes whenever one of its inputs changes, e.g., due to a new request, a change in the Reference Tree, or a change in the local Chunk State. The Reactor stops executing and puts itself to sleep whenever the Request Queue empties, or when it must block to wait for external changes, e.g., responses to requests on the Reference Tree or the relinquishing of locally-granted access privileges.

4.6 The Request Queue

As shown in Table 4.5, there are 6 types of requests that can be placed in the Request Queue, representing the local and Reference Tree versions of requests to gain Modify access to a chunk, to gain Read access to a chunk, or to garbage collect information related to the chunk.

Bit	Name	Definition
S	Sole	The Chunk Peer has the only copy of the chunk.
C	Copy	The Chunk Peer has a valid copy of the chunk.
X	External	Other Chunk Peers hold references to the chunk.
L	Local	The chunk is locally referenced.
T	Tree	The chunk is tree referenced.

Table 4.6: Major Chunk State bits

Bit	Name	Definition
M	Modify	A local application holds Modify privileges.
R	Read	A local application hold Read privileges.

Table 4.7: Privilege bits

Requests consist of a request type, the identifier of the requesting Chunk Peer, and a return direction. The return direction enables the Reactor to reply to requests. For requests that come from the Reference Tree, the return direction is the channel to which responses to the request should be forwarded, enabling responses to be forwarded along the Reference Tree one hop at a time without requiring further routing information. For local requests, the return direction is the application that made the request.

Recall from Section 3.3.4 that Reference Tree requests are prioritized by type and requester; the same is true of Requests that make it to the Request Queue. The highest-priority requests are the Local Modify and `E?` requests since they require the entire Reference Tree to cooperate to invalidate all but one copy of the chunk. Next are the Local Read and `C?` requests since they can be answered without the cooperation of the entire tree. At the lowest level are garbage collection requests since garbage collection runs asynchronously to applications and is not in the critical path of a computation.

4.7 Chunk State

The Chunk State component keeps track of 7 bits of state for each chunk. The 7 bits are divided into Major State bits, shown in Table 4.6, and Privilege bits, shown in Table 4.7. The Major State bits are used by the Reactor to determine the correct way to respond to a request, while the Privilege bits keep track of whether local applications have been granted chunk access privileges.

The Major State bits are sub-divided into two categories. The S, C, and X bits summarize the state of the chunk with respect to its Reference Tree. The X (eXternal) bit is set if any Channel Proxy is in the R, C, or G state; that is, the X bit is set if the Reference Tree extends beyond the local node. The C (Copy) bit is set when the Chunk Store contains a valid copy of the chunk. When the copy is invalidated for consistency reasons, the copy is deleted from the local Chunk Store and the C bit is cleared. The S (Sole) bit is set when the local Chunk Peer contains the only copy of the chunk in the Reference Tree. In other words, if any Channel Proxy is in the C or G state, then S is cleared.

The L and T bits are used to keep track of "liveness" of the Reference Tree by the Garbage Collector. They are described in detail in Section 4.9, but now it suffices to say that if either L or T are set, the chunk and its Reference Tree are considered alive by the Garbage Collector, while if they are both cleared, the chunk and its Reference Tree are candidates for reclamation.

All seven of the Chunk State bits serve to organize how the Reactor can respond to a top level request. For example, the Reactor can only grant Read privileges to a local application if $\mathrm{C} \cdot \overline{\mathrm{M}}$ is true, since the Chunk Peer needs a copy of the chunk to return and no other application can have Modify privileges. Similarly, the Reactor can only grant Modify privileges if $\mathrm{S} \cdot \overline{\mathrm{M}} \cdot \overline{\mathrm{R}}$ is true since the Chunk Platform's sequential consistency memory model requires that Modify privileges be granted to only one application at a time and that that application's Chunk Peer have the sole copy of the chunk. The Chunk State bits also help guard against garbage collection issues: a node cannot leave the Reference Tree if $\mathrm{S} \cdot \mathrm{X}$ is true, since one of the other nodes in the Reference Tree may need to read the sole copy of the chunk held locally.

Of the 32 possible combinations of Major State bits, the Chunk Exchange layer only uses 17. The Chunk States where S, C, and X are all zero indicate an invalid chunk ID since if the S, C, and X bits are all cleared, the Chunk Peer has a chunk ID that is not available locally nor over the Reference Tree. The Chunk Runtime reserves the case where all of the state bits are zero to indicate a "bad chunk ID"; the other three cases are unused and will signal a programming error if encountered.

The rest of the unused states derive from the overlap in meaning of the S and C bits. If S is set, the Chunk Peer has the sole copy of a chunk, which implies that the C bit must also be set. As such, any state where S is set and C is cleared is treated as an error state. Similarly, if a Chunk Peer has a copy of the chunk and it is the only node in the Reference Tree—that is, C is set and X is clear—then it must have the only copy of the chunk, implying S must also be set. Rather than having duplicate states, the Chunk Peer only uses the states where S and C are set and X is cleared.

4.8 The Reactor

The Reactor is implemented as an event loop that is activated whenever the Reference Tree, Request Queue, or Chunk State changes. On each execution, the Request Layer considers the Channel layer state, the Chunk State, and the top request of the Request Queue and does one of three things:

1. Fully handles the top request in the Request Queue.
2. Makes progress on the top request by sending messages to other Chunk Peers.
3. Nothing.

In the first case, the Reactor handles the request either by sending a message to the Channel layer that acts as an authoritative response to the request, by granting a locally running application the access privileges it desires, or by performing a garbage collection action that shrinks the Reference Tree. After handling the request, the Reactor deletes it from the Request Queue, and then moves on to the next request in the Request Queue or, if there are no more requests, goes back to sleep.

In the other two cases, the Reactor tries to make progress on handling the top request, then goes to sleep. The Reactor relies on the fact it will be re-awoken when its requests are responded to (since they change the Channel State of the Reference Tree) or when an application relinquishes a chunk access privilege (since releasing a privilege will alter the Chunk State). When woken, the Reactor runs through its loop again and attempts to make forward progress.

The Reactor's reactions to its inputs is encoded into a table, Table 4.8, whose rows are the major bits of the Chunk State and whose columns are the 6 types of requests allowed in the Request Queue. Each cell of the Reactor table contains a pointer to the function that handles that particular combination of major state and top request. The procedures,

Major State					Top Request					
S	C	X	L	T	Read	Modify	C?	E?	Leave	G?
0	0	0	0	0	E0	E0	E0	E0	E0	E0
0	0	0	0	1	Unused Chunk State: Bad Chunk ID					
0	0	0	1	0	Unused Chunk State: Bad Chunk ID					
0	0	0	1	1	Unused Chunk State: Bad Chunk ID					
0	0	1	0	0	E1	E1	FC	FE	GCLT	RQC
0	0	1	0	1	E1	E1	FC	FE	CLR	RQC
0	0	1	1	0	RQC	RQE	FC	FE	CLR	RQC
0	0	1	1	1	RQC	RQE	FC	FE	CLR	RQC
0	1	0	0	0	Unused Chunk State: same as SC					
0	1	0	0	1	Unused Chunk State: same as SC					
0	1	0	1	0	Unused Chunk State: same as SC					
0	1	0	1	1	Unused Chunk State: same as SC					
0	1	1	0	0	E1	E1	RSC	FRSE	GCLT	RQC
0	1	1	0	1	E1	E1	RSC	FRSE	CLR	RQC
0	1	1	1	0	GRR	RQE	RSC	FRSE	CLR	RQC
0	1	1	1	1	GRR	RQE	RSC	FRSE	CLR	RQC
1	0	0	0	0	Unused Chunk State: S without C					
1	0	0	0	1	Unused Chunk State: S without C					
1	0	0	1	0	Unused Chunk State: S without C					
1	0	0	1	1	Unused Chunk State: S without C					
1	0	1	0	0	Unused Chunk State: S without C					
1	0	1	0	1	Unused Chunk State: S without C					
1	0	1	1	0	Unused Chunk State: S without C					
1	0	1	1	1	Unused Chunk State: S without C					
1	1	0	0	0	E1	E1	E2	E2	GCD	E2
1	1	0	0	1	E1	E1	E2	E2	CLR	E2
1	1	0	1	0	GRR	GRM	E2	E2	CLR	E2
1	1	0	1	1	GRR	GRM	E2	E2	CLR	E2
1	1	1	0	0	E1	E1	RSE	RSE	GCRG	E2
1	1	1	0	1	E1	E1	RSE	RSE	GCRG	E2
1	1	1	1	0	GRR	GRM	RSC	RSE	CLR	E2
1	1	1	1	1	GRR	GRM	RSC	RSE	CLR	E2

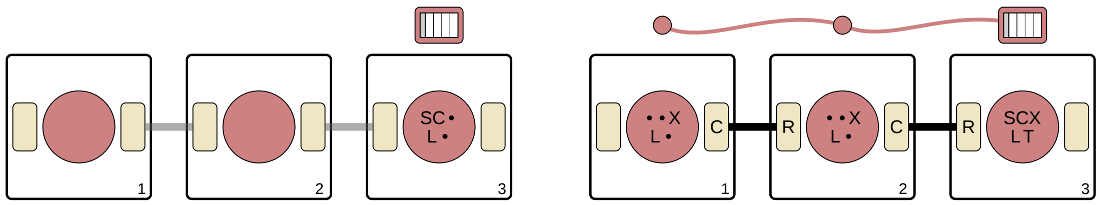
Table 4.8: The Reactor reaction table. Descriptions of the Reactor functions can be found in Table 4.9 while descriptions of Reactor errors may be found in Table 4.10.

Function	Listing	Description
FC	A.1	*Forward Chunk request* Forward received C? request towards copies of chunks.
FE	A.2	*Forward Evacuation request* Forward received E? request towards copies of chunks.
RQC	A.3	*ReQuest Chunk* Request a chunk from branches of the Reference Tree that have copies of the chunk.
RQE	A.4	*ReQuest Evacuation* Send evacuation requests to all branches of the Reference Tree that have copies of the chunk.
RSC	A.5	*ReSpond with Chunk* Respond to a request with a shared copy of the chunk.
RSE	A.6	*ReSpond by Evacuating chunk* Respond to a request by giving up the local copy of the chunk.
FRSE	A.7	*Forward or ReSpond by Evacuating* Make forward progress on an E? request, either by forwarding the request towards copies, or if all downstream copies have been invalidated, responding directly to the request.
GRR	A.8	*GRant Read* Grant Read privileges to a locally running application (as long as no local application has Modify privileges).
GRM	A.9	*GRant Modify* Grant Modify privileges to a locally running application (as long as no local application has Read or Modify privileges).
GCLT	A.10	*Garbage Collection Leave Tree* Leave the Reference Tree and clear out all chunk state.
GCD	A.11	*Garbage Collection Delete* Delete the only remaining copy of the chunk.
GCRG	A.12	*Garbage Collection Request Guarantor* Ask another Chunk Peer to guarantee the chunk for this Chunk Peer, so that this Chunk Peer can eventually leave the Reference Tree.
CLR	—	*Cancel Leave Request* Cancel a previously queued Leave request because of a mutation to the chunk graph.

Table 4.9: Reactor function descriptions. The Listing column indicates where the pseudocode implementation of the function may be found in Appendix A.

Error	Description
E0	Request on an unknown chunk ID
E1	Local request without local reference
E2	Tree request without a Reference Tree

Table 4.10: Reactor Error Types



(a) Node 3 creates a new chunk.

(b) State after expanding the Reference Tree to nodes 1 and 2.

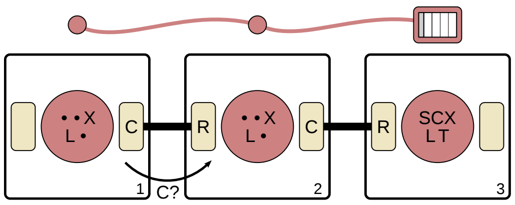
Figure 4.4: Chunk and Channel States during Reference Tree expansion.

described in Table 4.9 and written out in Appendix A, interact with the Channel Proxies, Chunk State component, and the Chunk Store.

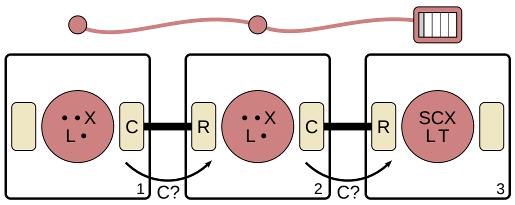
Certain combinations of Chunk State and request do not make logical sense. The error conditions, described in Table 4.10 describe why that particular cell is an error condition. The Chunk Runtime sends an error message to the application or requesting peer in response to one of the error conditions and then deletes the errant request.

4.8.1 Expanding the Reference Tree

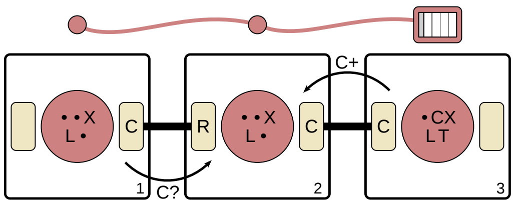
To gain intuition about how the Reactor works, consider the three nodes in Figure 4.4. Suppose that node 3 creates a new chunk. Newly created chunks start in the $S \cdot C \cdot \overline{X} \cdot L \cdot \overline{T}$ Chunk State since the node that created the chunk has the only copy ($S \cdot C$), no other node knows about the chunk yet ($\overline{X} \cdot \overline{T}$), and it is locally referenced since it was just created (L). Suppose that the Reference Tree expands to encompass the other two nodes. The Reactor does not handle Reference Tree expansions; instead it is notified by the Channel layer when new neighbors join the Reference Tree. As shown in Figure 4.4b, only the X and L bits are set on nodes 1 and 2, as they are members of the Reference Tree and reference, but do not have copies of, the chunk. Note that the expansion sets the X and T bits on node 3. The X bit is set because the Reference Tree now expands beyond just node 3. The reasons for



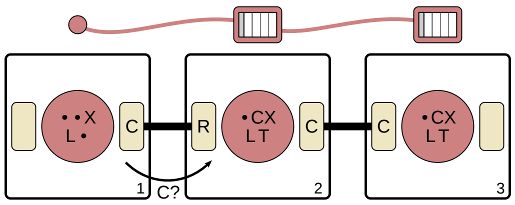
(a) Node 1 requests a copy of the chunk.



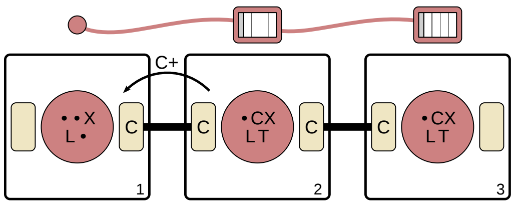
(b) Node 2 forwards node 3's request.



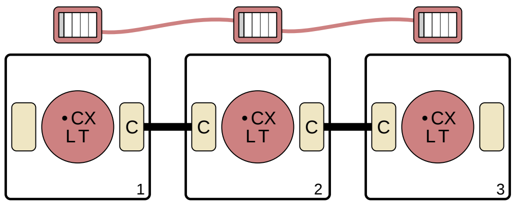
(c) Node 3 replies with a copy of the chunk, unsets its S bit, and updates its Channel State to C.



(d) Node 2 processes the response and updates its Chunk State.



(e) Node 2 replies to node 1 with a copy of the chunk.



(f) Node 1 processes the response, updates its Chunk State, and grants the local Read privilege.

Figure 4.5: Chunk and Channel States when node 1 requests a copy of the chunk.

setting the T garbage collection bit are explained in Section 4.9.1 and have to do with the fact that nodes 1 and 2 now rely on node 3's copy of the chunk.

4.8.2 Requesting Copies across the Reference Tree

Now, suppose that an application on the node 1 needs a copy of the chunk. When the application makes the `get(id)` call, the Chunk API adds a new Read request to node 1's Request Queue for that chunk ID. When the request bubbles to the top of the Request Queue, since the node is in the $\overline{S} \cdot \overline{C} \cdot X \cdot L \cdot \overline{T}$ Chunk State, the Reactor responds to the request by running the RQC (ReQuest Chunk) transition. The RQC transition sends a `C?` message towards copies of the chunks, as shown in Figure 4.5a and then blocks the node until it hears a response or a higher-priority request takes over. When the `C?` request reaches node 2, node 2 reacts by executing the FC (Forward Chunk request) transition. The FC transition forwards the C? request downstream and then waits for a response, as illustrated in Figure 4.5b.

When the C? request makes it to node 3 and bubbles up to front of node 3's Request Queue, node 3's Reactor executes the RSC (ReSpond with Chunk) transition. The RSC transition checks to make sure that no local application has Modify privileges. If an application does, the Reactor sleeps until the application relinquishes its privilege. Otherwise, if no application has Modify privileges, then the RSC transition sends a C+ message with a copy of the chunk back towards the return direction of the request. The RSC transition consumes the C? request, as shown in Figure 4.5c, letting node 3 move onto the next request to handle.

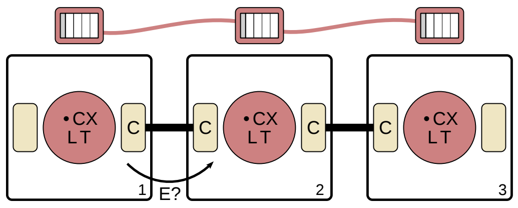
When node 3's C+ status message reaches node 2, the Channel layer on node 2 sets the C Chunk State bit, as displayed by Figure 4.5d. The change in the Chunk State wakes up node 2's Reactor. When it wakes up, the Reactor finds itself in the $\overline{\mathrm{S}} \cdot \mathrm{C} \cdot \mathrm{X} \cdot \mathrm{L} \cdot \mathrm{T}$ state with the same top request as when it went to sleep. It reacts to the new Chunk State by running the RSC transition, which forwards the chunk to the left using a C+ message, as demonstrated in Figure 4.5e, and then consumes the message.

When the C+ message reaches node 1, the Channel layer updates the Chunk State to $\overline{\mathrm{S}} \cdot \mathrm{C} \cdot \mathrm{X} \cdot \mathrm{L} \cdot \mathrm{T}$, leading to the state in Figure 4.5f, and wakes up the node's Reactor. Node 1's reactor runs the GRR (GRant Read) transition, which grants Read privileges to the application that requested them.

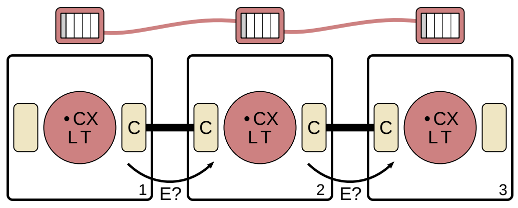
4.8.3 Maintaining Sequential Consistency

Recall from Section 3.4.1 that the Chunk Exchange Protocol implements sequential consistency by evacuating chunks towards the node whose applications requests the Modify privilege and granting the privilege when there is only one node with the chunk. To illustrate this, suppose that an application on node 1 in Figure 4.6 requests Modify privileges. When the Modify request makes it to the front of the Request Queue, the Reactor on node 1 executes the RQE (ReQuest Evacuation) transition, which sends E? requests towards all branches that have copies of the chunk, as Figure 4.6a illustrates.

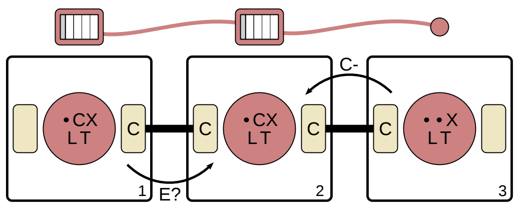
When the E? request reaches the node 2, node 2 executes the FRSE (Forward or ReSpond by Evacuating) transition. The FRSE transition attempts to make progress on an E? request forwarding the E? request, or if the copies in downstream branches have been invalidated, by responding directly to the request. Node 2's Reactor knows that the right branch of the



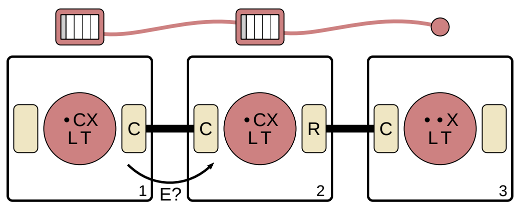
(a) Node 1 requests evacuation of the chunk.



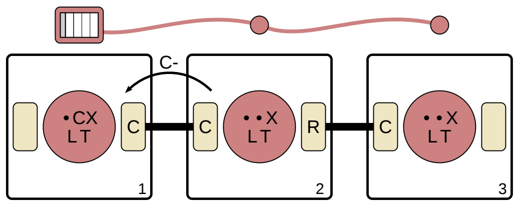
(b) Node 2 forwards node 1's request.



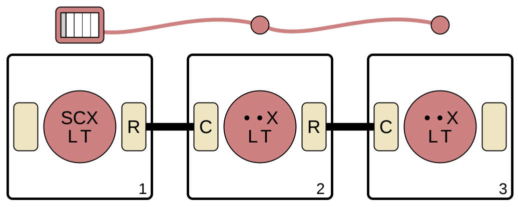
(c) Node 3 replies by deleting its copy of the chunk and sending it to node 2, unsetting its C bit.



(d) Node 2 processes the status message, updating its Channel State for node 3.



(e) Now that all downstream chunks have been evacuated, node 2 replies to node 1 by deleting its copy of the chunk, unsetting its C bit, and sending the chunk to node 1.



(f) Node 1 processes the status message, updates its Chunk and Channel States, and grants the local Modify privilege.

Figure 4.6: Chunk and Channel States for the process of granting a Modify request.

Reference Tree still has a copy, so the FRSE transition executes the FE (Forward Evacuation request) branch, which forwards the E? request to the right node, as shown in Figure 4.6b.

When the E? request reaches node 3, the node's Reactor also executes the FRSE transition. In this case, the FRSE transition executes the RSE (ReSpond by Evacuating chunk) branch, since there are no downstream nodes to which to forward the E? request. The RSE branch waits until local applications relinquish all of their access privileges. When they have, node 3 invalidates its local copy of the chunk (unsetting the C bit of Chunk State) and then responds to the original request with an C- message, as demonstrated in Figure 4.6c.

When node 3's C- message reaches node 2, node 2's Channel layer sets node 3's channel to R (Figure 4.6d) and then forwards the request to the Reactor. Node 2's Reactor re-runs the FRSE transition, which now runs the RSE branch since the downstream nodes no longer have copies of the chunk. Like node 3, node 2 deletes its local chunk copy, clears its C bit, and then forwards the chunk to the left using a C- message, as Figure 4.6e shows.

When the C- message reaches node 1, the Channel layer resets the Channel State for the Reference Tree to R, which causes the S bit to be set in the Chunk State, leading to the configuration shown in Figure 4.6f. When the node 1's Reactor wakes up, it finds itself in the $S \cdot C \cdot X \cdot L \cdot T$ state and correspondingly runs the GRM (GRant Modify) transition to grant the Modify privilege to the application that requested it.

4.9 Garbage Collection

Distributed garbage collection in the Chunk Platform faces two main challenges. The first is that of maintaining connectivity of Reference Trees. Since Reference Trees connect all nodes that reference a chunk, a node whose applications no longer use a chunk may be required to stay in the Reference Tree since it is on the path between other nodes that do have live references to the chunk. As such, the Chunk Platform must safely determine when a particular node can leave the Reference Tree safely.

The second challenge is that of asynchrony. Given that modern computing substrates may be arbitrarily large, it is not feasible to perform globally synchronous garbage collection. Instead, garbage collection processes that may pause a single node must run in parallel with other nodes that are actively mutating the global chunk graph. The Chunk Platform handles asynchrony by being conservative and keeping chunks around until it can prove that it will no longer need them.

4.9.1 Leaving the Reference Tree

The Chunk Platform's garbage collection strategy relies on Chunk Peers leaving the Reference Tree so that the Reference Tree shrinks down to one node that then deletes the chunk. The key difficulty implementing this strategy is determining when a particular node can leave the Reference Tree. There are three reasons why a node must stay in the Reference Tree:

Hostage The node is in the middle of the Reference Tree and provides connectivity for other nodes.

Locally Referenced The chunk is in use by applications running on the node.

Tree Referenced The chunk is referenced by applications on other nodes.

The first constraint comes directly from the Chunk Platform's garbage collection strategy: hostage nodes must remain in the Reference Tree until they become leaves of the Reference Tree. To implement the hostage requirement, the Request Queue rejects any Leave requests on hostage nodes. Hostage nodes are unavoidable in the Chunk Platform, but it is possible to exploit the tree structure of Reference Trees to minimize the number of hostages by moving computations around so that nodes whose applications actively reference the chunk are in the center of the Reference Tree.

In contrast, the last two constraints come from dynamic configuration of the chunk graph rather than that of the Reference Tree. The locally referenced and tree referenced properties are transitive, meaning that if a given chunk is locally or tree referenced, then all of its referents are also locally or tree referenced. As such, keeping track of these constraints requires exploring the chunk graph and propagating the reference properties. The Chunk Platform maintains these constraints with a combination of a local "stop-the-world" garbage collector and the L and T bits in the Chunk State.

Locally Referenced Chunks

Locally referenced chunks are those that are in use by an application running on the node. In other words, local referencing is the standard concept of liveness in garbage collected systems.

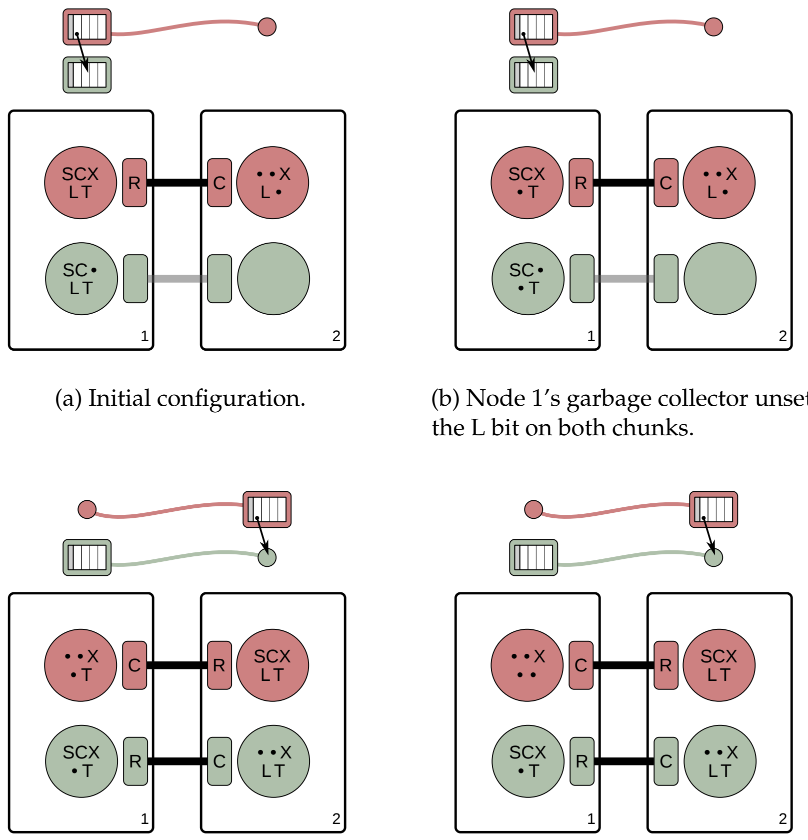
The Chunk Peer keeps track of local references through the L bit in the Chunk State component. As a base case, the L bit is set on any chunk in the garbage collector's "root set" of live chunks. This set is modified by applications using the `gc_root_add(id)` and `gc_root_remove(id)` functions of the Chunk API.

The L bit is maintained two ways. First, the L bit is set or cleared by a standard "mark and sweep" garbage collector, providing a periodic ground truth of liveness. Second, whenever the Chunk Peer processes a chunk copy whose L bit is set, it automatically sets the L bit of all of its referents. This lets us handle asynchronous mutation of the chunk graph during garbage collection since it propagates the L bit as applications walk through the chunk graph or chunks are transferred by the Channel Layer through the Chunk Peer. This maintenance strategy is conservative because only the periodic runs of the garbage collector can clear the L bit. However, conservatism is warranted since leaving the Reference Tree destroys information.

Tree Referenced Chunks

Tree referenced chunks are those that are live on a particular node in order to ensure referential integrity of the chunk graph for other nodes. The simplest example of a tree referenced chunk is an externally-referenced sole copy of a chunk held at a node that wishes to garbage collect the chunk and leave its Reference Tree. If the node just deletes the chunk, the node will break the referential integrity of links on other nodes pointing to that chunk. As such, the node holding the chunk must stay in the Reference Tree until it gives a copy to another node in the Reference Tree.

More generally, any externally-referenced chunk for which a node has a locally valid copy is considered tree referenced, since those chunks can be used to satisfy external `C?` requests from the Reference Tree. Moreover, every chunk linked by a tree referenced chunk is tree referenced since the initial tree referenced chunk may point to a sub-graph of chunks that only the node knows about.



(a) Initial configuration.

(b) Node 1's garbage collector unsets the L bit on both chunks.

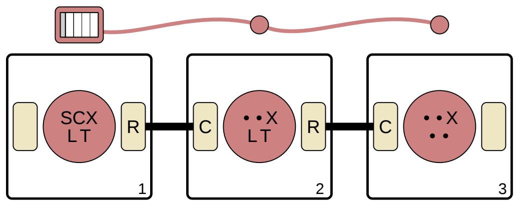
(c) Node 1 evacuates the red chunk, extending the green Reference Tree.

(d) After another garbage collection cycle, the red chunk can be reclaimed on node 1.

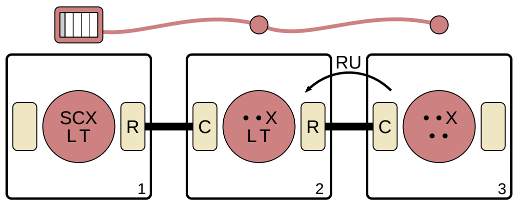
Figure 4.7: The T bit protects against premature collection of sub-graphs of chunks.

Like the L bit, the tree referenced property is a transitive property maintained using the T bit of the Chunk State component. The root set of chunks are those Chunks where the C and X bits set; the garbage collector also sets the T bit on the children of chunks with the T bit set. As for the L bit, and for the same reasons, the T bit is set by both the garbage collector and by the Chunk Peer as it steps through the chunk graph, but it is only cleared by the garbage collector.

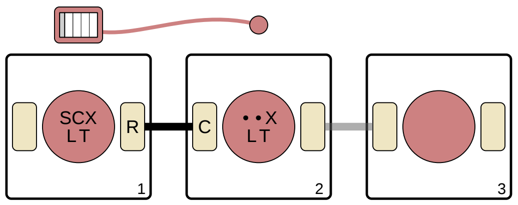
Figure 4.7 illustrates the T bit and how it protects a sub-graph of chunks from being prematurely collected. Node 1 has the sole copy of the red chunk, which it has modified to link to the green chunk. If, as shown in Figure 4.7b, node 1's garbage collector determines that the chunks are no longer locally referenced, it will clear the L bit on both chunks. Since no other node knows about the green chunk, if it were not for the T bit, node 1's



(a) Node 3's local garbage collector unsets its L and T bits.



(b) Node 3 messages node 2 it's intent to leave the Reference Tree.



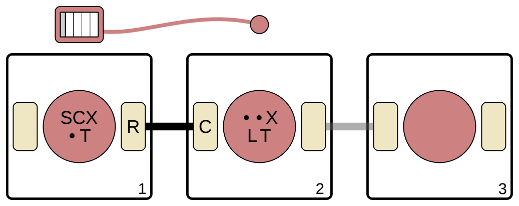
(c) Configuration after node 3 leaves the Reference Tree.

Figure 4.8: Garbage collection example for a node with no chunk copy.

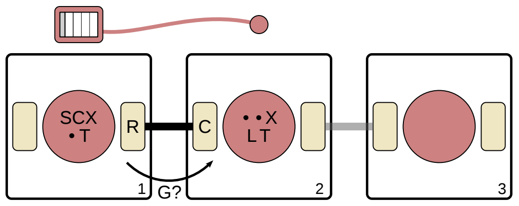
Reactor would immediately delete the green chunk, which would break node 2's ability to de-reference the green chunk. The T bit keeps node 1 in the green chunk's Reference Tree. When node 1 evacuates its copy of the red chunk (Figure 4.7c), the Reference Tree expansion bootstrap procedure informs node 2 of the existence of the green chunk. By extending the green Reference Tree to node 2, both the C and X bits get set for the green chunk on node 1, maintaining the T bit independently of the red chunk. When the garbage collector runs again on node 1, all of the red chunk's garbage collection bits get cleared (Figure 4.7d), allowing the red chunk to be garbage collected.

4.9.2 Example

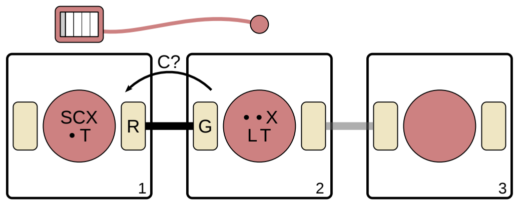
To build intuition for how the Reactor handles garbage collection, consider Figures 4.8 and 4.9. Figure 4.8 shows a simple example of leaving the Reference Tree. Suppose that the local garbage collector on node 3 decides that no application references the chunk. As illustrated in Figure 4.8a, the garbage collector clears the L bit to indicate the chunk is no longer live and puts a Leave request in node 3's Request Queue. The change in Chunk State wakes up the Reactor. When servicing the Leave request, the Reactor executes the GCLT (Garbage Collection Leave Tree) transition. The GCLT transition leaves the Reference Tree by emitting an RU message and clearing all Reference Tree state, as shown in Figure 4.8b.



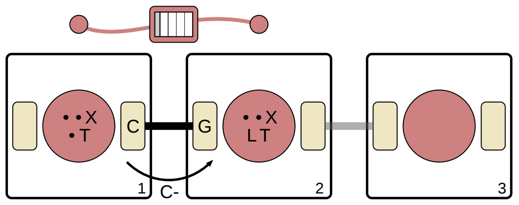
(a) Node 1's local garbage collector unsets its L bit.



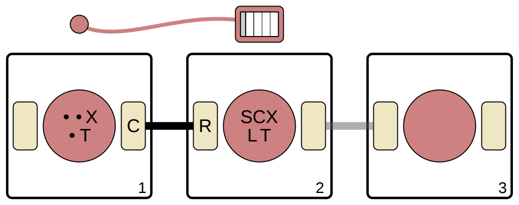
(b) Node 1 must get rid of its copy before it can leave the Reference Tree, so node 1 asks node 2 to guarantee the chunk copy.



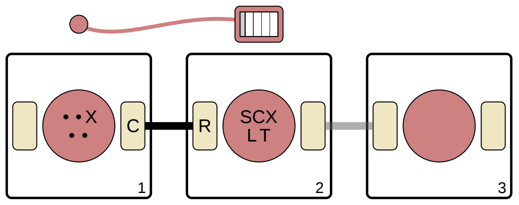
(c) Node 2 guarantees the chunk.



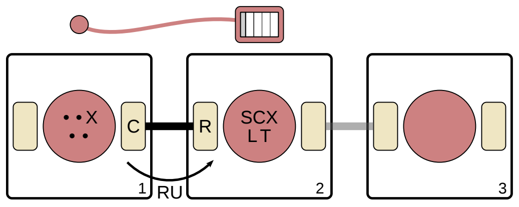
(d) Node 1 gives up its copy of the chunk.



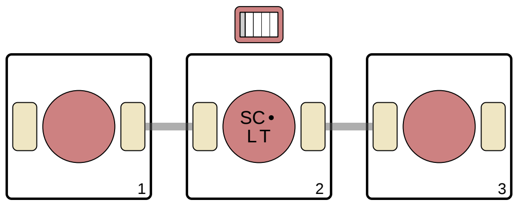
(e) The T bit keeps Node 1 in the Reference Tree.



(f) After node 1's garbage collector runs and clears the T bit, node 1 is the same state as Node 3 in Figure 4.8a.



(g) Node 1 leaves the Reference Tree.



(h) Node 2 is the only node left in the Reference Tree.

Figure 4.9: Garbage collection example for a node with a chunk copy.

When the Channel Layer on node 2 processes the RU request, it invalidates node 2's Channel Proxy, resulting in the Reference Tree configuration shown in Figure 4.8c.

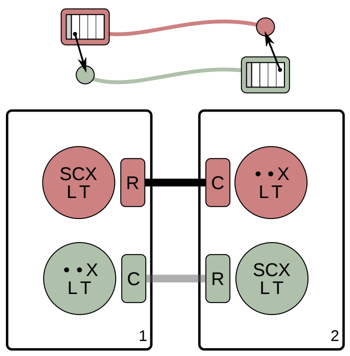
Figure 4.9 shows a more complicated garbage collection scenario involving evacuating a copy of a chunk. Suppose that node 1's garbage collector decides that the chunk is dead and clears the L bit as illustrated in Figure 4.9a. Even though the chunk is no longer locally referenced, node 1 cannot leave the chunk's Reference Tree because the T bit is set. When node 1's Reactor wakes up, it runs the GCRG (Garbage Collection Request Guarantor) transition, which attempts to find a guarantor that will take a copy of the chunk, eventually enabling node 1 to leave the Reference Tree. The GCRC transition sends a G? request to node 2, as shown in Figure 4.9b. Node 2 handles the G? by running the RQC transition to request the chunk from node 1, as Figure 4.9c. The Channel layer on node 2 records the fact that node 2 is guaranteeing the chunk so that node 2 does not attempt to leave the Reference Tree until it finishes its guarantee.

When node 1 receives the C? request, it runs the RSE (ReSpond by Evacuating chunk) transition. As shown in Figure 4.9d, the RSE transition enables node 1 to transfer its copy of the chunk to node 2. Node 1 still cannot leave the Reference Tree until the garbage collector runs and clears the T bit, as shown in Figure 4.9e. When it does, as shown in Figure 4.9f, node 1 is in the same state as node 3 started in in Figure 4.8. Like node 3 in the first example, node 1 leaves the Reference Tree in the same way, as shown in Figure 4.9g.

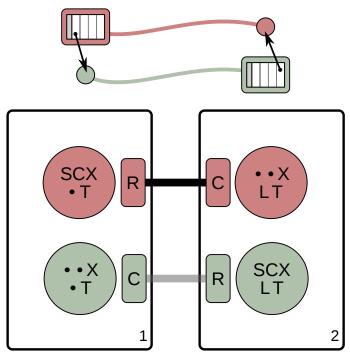
When node 1 leaves the Reference Tree, as Figure 4.9h illustrates, only node 2 is left in the Reference Tree. The next time that node 2's garbage collector runs, it will clear the T bit since no Reference Tree references the chunk. Later, if node 2's local garbage collector decides that the chunk is dead, it unsets the L bit, enabling reclamation of the chunk's resources. When the Reactor runs after the garbage collector determines that the chunk is dead, the reactor executes the GCD (Garbage Collection Delete) transition which deletes the copy of the chunk and cleans up all of the local state held by the chunk.

4.9.3 Handling Loops

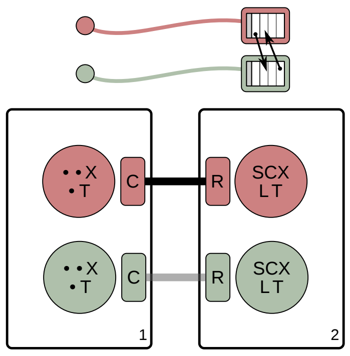
Reference loops are the bane of resource reclamation systems. While handling local reference loops is easy with a stop-the-world garbage collector, distributed garbage collection systems often have difficulty collecting loops that span more than one node [5].



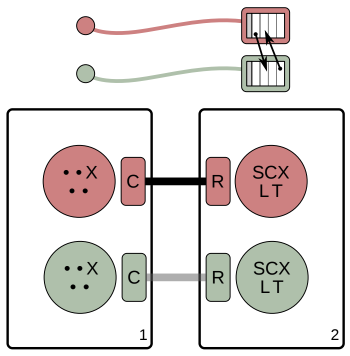
(a) Reference loop spanning two nodes.



(b) Even after clearing the L bit, node 1 has a T-bit loop.



(c) Evacuating the red chunk to node 2 clears the C bit on node 1.



(d) After node 1's garbage collector runs again, the T bits are clear.

Figure 4.10: A cycle spanning multiple nodes.

The key to collecting distributed reference loops is finding a way to break the loops between the nodes. In the Chunk Platform, distributed loops are loops formed by chunks in Chunk States where $\overline{\mathrm{L}} \cdot \mathrm{T}$ is true, since chunks with the L bit set are locally live and won't be touched by the garbage collector, while chunks in Chunk States where $\overline{\mathrm{L}} \cdot \overline{\mathrm{T}}$ is true are not referenced at all and can be reclaimed without further ado. Since the T bit is set on chunks where $\mathrm{C} \cdot \mathrm{X}$ is true, the Chunk Peer breaks loops by evacuating chunks to other nodes in the Reference Tree. By evacuating chunks, the Chunk Peer reduces the set of chunks that have the C Chunk State bit set, transitively reducing the set of chunks that have the T Chunk State bit set.

Consider the cycle in Figure 4.10a that spans two nodes. Suppose that node 1's garbage collector decides that both chunks are dead, leading to the T-bit loop in Figure 4.10b. If node 1 evacuates the red chunk to node 2, node 1 can clear the red chunk's C bit, as shown in Figure 4.10c. When node 1's garbage collector runs again, it will clear the T bit on both chunks since no $C \cdot X$ or T chunks point to either of them, leading to the situation in Figure 4.10d. As this point, the loop is completely broken and node 1 can leave both chunks' Reference Trees.

Chapter 5

Applications

A main claim of this thesis is that structured computing models like the Chunk Model make it easier to build and maintain applications, and the run-time systems that support those applications, on modern computing substrates. The evaluate that claim, this chapter details three applications built on top of our Chunk Platform implementation of the Chunk Model.

The first application, SCVM, serves as a vehicle for evaluating the general applicability of the Chunk Model as a compute platform. SCVM demonstrates the claim that the Chunk Model is suitably application-generic by supporting a general-purpose compiler as well as two SCVM-based applications that successfully use SCVM's machine model to achieve their tasks. The second application, Tasklets, uses the Chunk Platform and SCVM to build infrastructure for offloading small computation tasks to the cloud. Tasklets further demonstrate the application-generic nature of chunks by proposing a new model for cloud computing. The last application, ChunkStream, serves as a vehicle for chunks as a data-only model. ChunkStream demonstrates the claim that the Chunk Model is transparent and can be adapted to real-world uses of complex data types.

5.1 SCVM

SCVM is a chunk-oriented virtual machine that uses the CVM data structure of Section 2.3.2. As an evaluation mechanism, SCVM serves two purposes. First, it shows chunks to be a suitable foundation for computation. Second, it serves as an example application that stresses the Chunk Platform, and indeed drove much of the development of system-level features like sequential consistency and garbage collection.

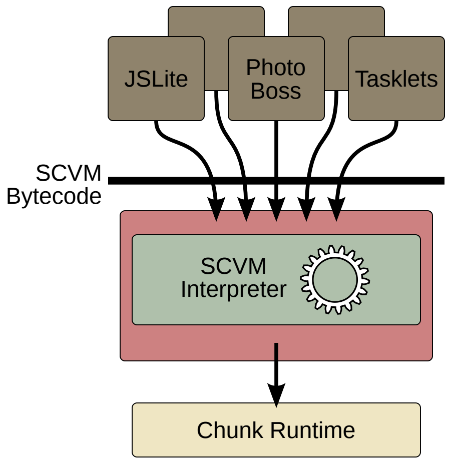


Figure 5.1: The SCVM ecosystem.

Figure 5.1 illustrates the SCVM ecosystem. Applications written for SCVM use SCVM's structure-preserving, chunk-based bytecode to express computations. In turn, SCVM sits on top of the Chunk Platform and makes use of the Chunk Platform's features to distribute computations by distributing chunks among the many nodes in the computation substrate.

5.1.1 The SCVM Virtual Machine Model

SCVM is a stack machine that uses the CVM data structure for its run-time state. SCVM augments the CVM data structure of Figure 2.6 in two ways. First, since it is a stack machine, SCVM maintains an operand stack as a separate data structure linked from the main Thread chunk. Making SCVM a stack machine is a choice born of implementation convenience. All of the structures and lessons learned from SCVM's implementation would also apply to a chunk-based register machine. Second, SCVM adds "escape hatches" to allow SCVM programs to leave the virtual machine environment and make use of external libraries. Again, this is for implementation convenience, as the escape mechanism allows the SCVM interpreter to (1) directly use the chunk-based data structure libraries provided by the Chunk Platform and (2) use shims to adapt third-party libraries to operate on chunks, rather than re-implementing those libraries in SCVM bytecode.

A unique feature of SCVM is its bytecode. SCVM bytecode instructions are strings that each fit inside the slot of a chunk. During execution, SCVM instructions may (1) access and modify chunks linked to by the root Thread chunk and (2) modify the stack. SCVM instructions obtain their operands from one of three places:

1. From an immediate value embedded in the instruction,
2. From values popped off the machine stack, and
3. From the code chunk itself.

In general, the immediate value is a scalar value. SCVM provides all of the usual binary operations, branches, jumps, and procedure call primitives. Unlike conventional instruction sets, SCVM does not provide instructions to read or write memory. Instead, SCVM provides instructions for creating, reading, and writing chunks. SCVM does not provide mechanisms for deleting chunks since it uses the Chunk Platform's garbage collection features to determine when particular chunks are no longer in use by an application.

In contrast to traditional straight-line bytecodes, SCVM's bytecode adheres to our Structural Transparency Principle and preserves the basic block structure of computations in the chunk graph. It does this with two bytecode features:

1. Jumps and branches may only jump to the beginning of a chunk.
2. Links embedded in the bytecode chunks are interpreted as `push link` instructions.

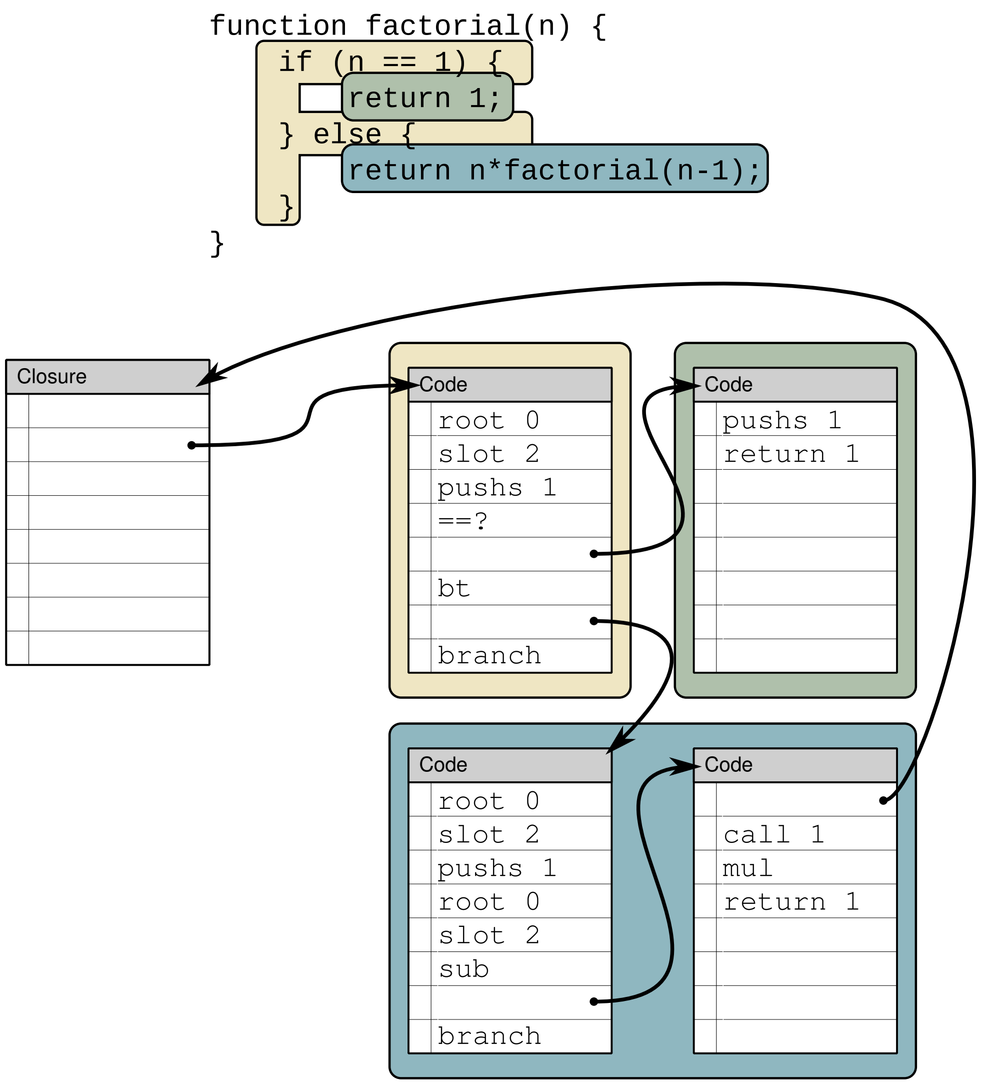
The first feature forces basic blocks to start at the beginning of chunks. The second rule explicitly exposes jump targets as chunk link targets, exposing the basic block structure as chunk structure.

For example, Figure 5.2 shows a detailed view of the chunk bytecode for `factorial(n)`. Like most recursive functions, `factorial(n)` consists of three different parts: the base case, the recursive case, and the code that determines which case should be invoked. Due to SCVM's bytecode rules, the code for `factorial(n)` breaks neatly into three groups of chunks each corresponding to the three different parts of the function. Note that the recursive case spills over into two chunks since the bytecode is longer than the relatively small chunks used in the diagram.

The full specification for the SCVM virtual machine can be found in Appendix B.

5.1.2 JSLite

JSLite is a compiler and run-time environment that targets SCVM. In contrast to SCVM itself, which is chunk-centric, JSLite completely hides chunks from programmers. JSLite,



```
function factorial(n) {
  if (n == 1) {
    return 1;
  } else {
    return n*factorial(n-1);
  }
}
```

Figure 5.2: SCVM bytecode for factorial(n). SCVM's bytecode preserves the basic block structure of the computation: the base case is shaded green, the recursive case is shaded blue, and the code that determines which case will be used is shaded yellow.

by providing a familiar language and set of libraries that make use of chunks and chunk features without showing that the underlying implementation is in chunks, indicates that the Chunk Model can be used for general-purpose computing tasks without requiring the end-user programmer to understand whole chunk computing model.

JSLite is a subset of the JavaScript language. Like JavaScript, JSLite is a scoped, closure-based language. The JSLite programming model fits well with the environment-based model exposed by SCVM. JSLite includes a standard library that implements the primitive JavaScript types, including arrays, strings, and objects. The standard library is chunk-aware and provides reasonably fast, variable-sized objects in the face of fixed-sized chunks and loss of random access memory. For example, the Array implementation provides $O(\log(n))$ worst-case random indexing with fast appends by gradually building n-ary search trees for elements as those elements are appended.

The JSLite compiler and standard library make full use of the Chunk Platform's facilities. For example, rather than implementing its own garbage collector, JSLite leverages the distributed garbage collector of the Chunk Peer to garbage collect objects as they fall into disuse. JSLite programs can make use of multiple SCVM interpreters running on multiple Chunk Runtimes to provide a parallel shared memory programming environment; this functionality relies heavily on the shared-chunk primitives exposed by the Chunk API.

To aid programmers in the shared memory environment, JSLite's standard library includes the parallel library. The parallel library implements a selection of parallelism primitives that enable JSLite computations to spawn new threads of computation on other nodes and synchronize with those threads. For example, the spawn(fn, args...) spawns a computation on another node, while the parallel.Barrier prototype object provides a simple synchronization barrier.

Appendix C contains big_jacobi.js, a JSLite-based implementation of the Jacobi relaxation method of solving a system of linear equations. As we co-developed the JSLite compiler, SCVM, and big_jacobi.js, we attempted to push as much complexity as possible away from the programmer. As a result, big_jacobi.js is a straight-forward implementation of Jacobi relaxation that uses nested Arrays for matrices and barriers for synchronization and that requires no Chunk Platform-specific workarounds. The Jacobi program stresses the entire Chunk Platform, especially the Chunk Exchange Protocol, since it makes heavy use of shared chunks. Many bugs and race conditions in the initial versions of the Chunk Exchange Protocol were exposed by simply running big_jacobi.js.

5.1.3 Photo Boss

Web developers partition their applications to trade-off the tensions between having an interactive user interface, typically implemented as operations inside the browser, and using the processing power of machines in a data center. PhotoBoss, a suite of photo editing and organization web apps, explores an alternative model of cloud computing where web browser-based clients and data center-located servers use shared SCVM code to dynamically migrate computations from clients to servers and back based on interactivity and computational power requirements. In other words, rather than the fixed partitioning of web apps between strictly server code and strictly client code, PhotoBoss allows fluid sharing of computations between the client and the server using SCVM and the Chunk Platform as backing technologies.

In PhotoBoss, a web app client initializes by fetching code from a data center to execute locally, but over time may either (1) upload code back to the data center to take advantage of extra processing power or (2) download more code to run locally to provide a richer user experience. For example, the web client parts of PhotoBoss applications operate on a proxy images and then upload code to the server representing exactly the steps the user took to edit the proxy and apply it to high-resolution versions of that image.

The PhotoBoss suite of applications includes a photo organization tool, Quickr, shown in Figure 5.3 and a photo manipulation tool, PhotoChop, shown in Figure 5.4. Quickr and PhotoChop both use chunks to represent both image data and SCVM-based computations.

The data structure holding each photo contains a tree of chunks representing multiple resolutions of the photo. Quickr exploits the chunk tree to choose which photo resolution is appropriate to show the user based on the client's screen resolution.

PhotoChop represents photo filters as SCVM closures. When a web client connects to the PhotoChop server, the client bootstraps itself by downloading and executing the JavaScript SCVM implementation, which, in turn, references and downloads the filter implementations from the server. As the user experiments with various filter combinations, PhotoChop generates and executes SCVM bytecode representing the user's chosen filters and parameters. Since PhotoChop may run on a computationally weak web client, in order

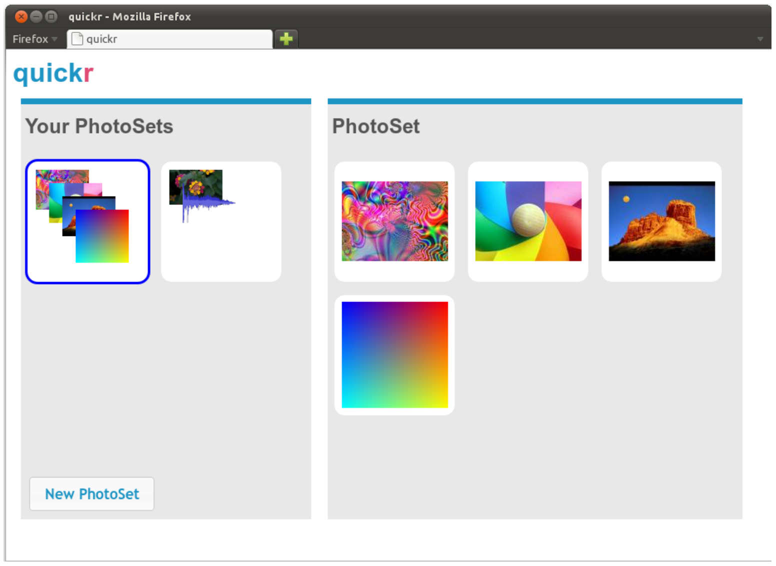


Figure 5.3: Screen shot of the Quickr photo organization tool.

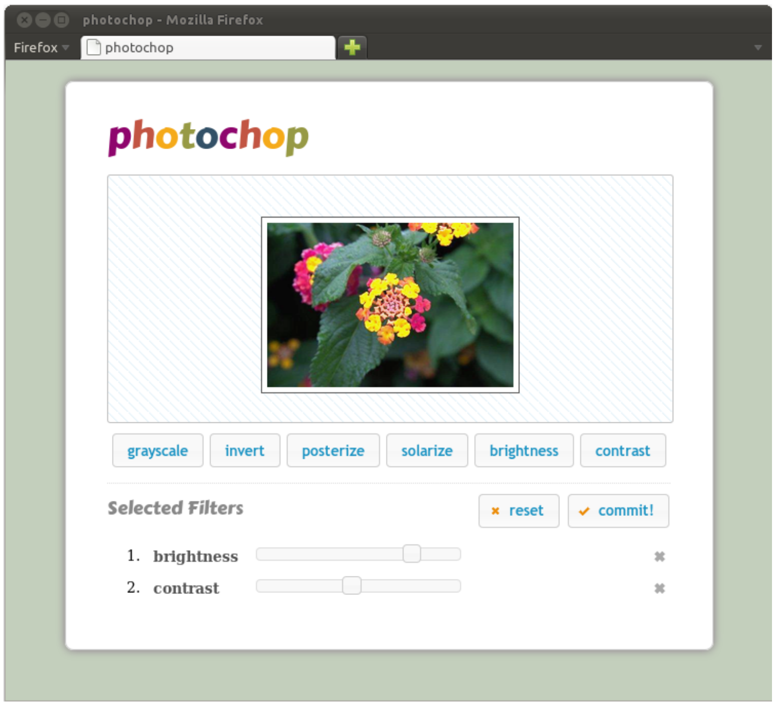


Figure 5.4: Screen shot of the PhotoChop photo editing tool.

to enable interactive experimentation with filters, PhotoChop normally only operates on small resolution versions of photos. When the user finishes her experimentation, PhotoChop generates “final” SCVM bytecode to apply the filters to all resolutions of the photo. Normally, the web browser chooses to migrate the code to a fast remote server to operate on the high resolution photos, but depending on communication costs, PhotoChop may opt to run all of the bytecode locally, or split computation between local and remote servers.

5.2 Tasklets

Currently, there are two popular models for selling and accounting for use of cloud computing resources: (1) charging per usage hour for generic virtual machines, e.g., as in Amazon EC2 [8] and Windows Azure [70], and (2) charging for fine-grained service requests, e.g., as in Google App Engine [42]. While the virtual machine approach offers maximum flexibility with respect to the programming model, coarse-grained accounting restricts the kinds of jobs that may run. Because virtual machines require significant initial setup, they are best suited for large numbers of identical tasks that (1) may be combined to amortize machine setup and maintenance, and (2) may consume every rented minute of computation, as unused capacity goes to waste. In contrast, the fine-grained accounting model of Google App Engine enables small tasks to take up only small amounts of rented time, but requires the programmer to structure her application around the particular fine-grained request/response interfaces of Google App Engine.

The PhotoBoss application of the previous section hints at another model for cloud computing: trading the execution of small tasks between clients with tasks to perform and servers that may perform those tasks for a price. The core enabler of this new cloud programming model is the *Tasklet*. A Tasklet is an SCVM Thread packaged with metadata concerning the cost and performance requirements of the task. Tasklets are supported by *Tasklet Containers* that may execute Tasklets in a local SCVM interpreter as well as offload Tasklets to third-party Tasklet Containers running on other hosts. Tasklet Containers may run as new cloud services (e.g., Tasklets as a Service), in idle time on top of existing cloud services (e.g., as a process that takes up the remaining slack time on an already running Amazon EC2 instance), or in idle time on locally available computing hardware (e.g., as in resource foraging systems). Since SCVM structures are self-contained, it is possible to migrate a computation between Tasklet Containers by pausing the computation, shipping the Tasklet's chunks to the remote Container, and resuming computation with the transferred chunks. In contrast to a virtual machine that needs to be appropriately configured before use, all Tasklet Containers are "blank slates" that rely on a Tasklet linking to all of the data and libraries that it needs in order to execute.

Tasklets enable generic computation at fine-grained scales. Compared to the Amazon EC2 virtual machine model, the Tasklet model allows clients to offload relatively small tasks. Compared to the Google App Engine model, the Tasklet model is application-generic and gives the programmer more flexibility in choice of programming frameworks. Thus, Tasklets fill the gap between request-based models and virtual machine-based models.

5.2.1 Tasklet Accounting with Chunks

Proper accounting for resource usage is crucial when building a system that charges for the execution of tasks. The fixed-size nature of chunks enables the Tasklet layer to account for resource usage by counting chunks. For example, bandwidth consumption is measured as the number of chunks transferred between two hosts while computation consumption is measured as the number of chunks executed. While it is possible to account for resource consumption using multiple different metrics, e.g., bytes for network transfers and milliseconds for compute time, using a single unit to measure resource usage makes it easier to build an economy since there is only one currency to trade.

The chunk-based foundation for Tasklets encourages fine-grained accounting by encouraging the use of fine-grained, chunk-based data structures. Similarly, the fined-grained nature of Tasklets enables us to make use of large libraries (e.g, for image filtering or speech recognition) or large data sets, but only transfer the specific parts of the libraries or data sets necessary to complete the Tasklet's particular computation.

While recording run-time usage is important for simple accounting, a client may wish to predict costs before making a decision to offload a Tasklet to a particular Container. Static analysis or Tasklet execution history can help predict how much computing time is required to compute a Tasklet. For example, for the factorial(n) function illustrated in Figure 5.2, a static analyzer can determine an exact solution for the number of chunks executed. The factorial(n) function executes two chunks for the base case of $n = 1$ and three chunks for $n > 1$, leading to a closed form execution time of $3(n-1)+2$ chunks.

For computations where analysis is more difficult, Tasklets offer graceful recovery for inaccurate analysis. For example, if a Tasklet exhausts its share of a Container's resources before completing its computation, the Tasklet may be migrated to another Container where it may resume—rather than be killed after a certain timeout, as is done in Google App Engine.

5.2.2 Trading Tasklets

Using Tasklets as a computational model requires applications to find appropriate Containers to execute Tasklets as well as to propagate their excess capacities to other applications. The core architectural model is that of a trading service. In contrast to trading services introduced by Jini [88] or CORBA [75] that trade functional components, the Tasklet layer only trades one good: the execution of Tasklets.

Figure 5.5 illustrates the components and the basic messages involved in trading Tasklets. The Tasklet Trading Service mediates between offers and requests for computational capacity. Tasklet Containers advertise their available resources, either (1) as a Tasklet capacity, for services that are metered by resource usage or (2) as a time window with a deadline, e.g., for the termination time of an Amazon EC2 instance running a Tasklet Container in the excess of its hour, as well as the cost of using the Tasklet Container. Computing capacity is denoted in chunks and costs depend on the economic model that is realized by the Tasklet federation. If a Tasklet Container offers execution of Tasklets on third parties, capacities for the third-parties can be propagated as well. Candidate Containers are represented with enough information for applications to contact them, e.g., an IP address and port number, along with additional information like service provision contracts. An application queries the Tasklet Trading Service in order to obtain references to Containers that can compute a Tasklet. Once the application chooses a Tasklet Container, it interacts directly with the Tasklet Container. The Tasklet Container updates its capacity at the Tasklet Trading Service as it accepts and completes Tasklets.

The Tasklet Trading Service opens Tasklets to different economic models. The simplest economic mode is that of free sharing of excess capacity, e.g., between users in the same administrative domain. Alternatively, since free-riders will exist in any system [56], a slightly more advanced economic model may require reciprocal sharing of capacity. More precisely, Tasklets of a user u are only allowed to be executed at a remote Tasklet Container

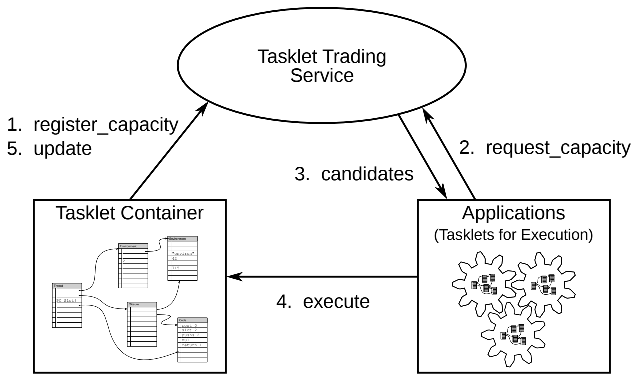


Figure 5.5: Tasklet Trading Service

if the ratio between the Tasklets that u's Container has executed on behalf of other users, o, and the Tasklets that u has remotely executed, r, is greater than a threshold, t. In other words, if $o/r > t$ holds the user may execute Tasklets with other users' Containers. Lastly, the Tasklet Trading Service may operate using currency, both virtual or real. It is unclear what the best Tasklet economic model is; it is fertile ground for future work.

5.3 ChunkStream

The ChunkStream video system implements a video playback library using the ChunkStream data structure of Section 2.3.1. While the general ideas behind the ChunkStream structure remain the same, in order to build a real system, two adjustments had to be made to it to handle real video streams. First, the ChunkStream system augments the FrameData chunks with additional information to handle non-linear inter-frame dependencies in video codecs. Second, since most video clips include other streams of data, the ChunkStream system adds non-video streams to the ChunkStream data structure.

5.3.1 Codec Considerations

In traditional video files, raw data is organized according to a container format such as MPEG-TS, MPEG-PS, MP4, or AVI. ChunkStream's IndexTrees, backbones, and Lane-Markers serve to organize raw encoded streams and, as such, may be considered to be a chunk-based container format.

Container formats offer many advantages over raw codec streams. Most formats allow a single file to contain multiple streams, such as a video stream and one or more audio streams, as well as provide different features depending on the environment. Some formats, like MPEG-TS, include synchronization markers that require more bandwidth, but tolerate packet loss or corruption, while others are optimized for more reliable, random-access media. However, at its core, the job of the container format is to present encoded data in the order in which the decoder needs it.

This is especially important for video codecs that use inter-frame compression techniques because properly decoding a particular frame may depend on properly decoding other frames in the stream. For example, the H.264 codec [2] includes intra frames (I-frames) that can be decoded independently of any other frame; predictive frames (P-frames) that depend on the previously displayed I- or P-frames; and bi-predictive frames (B-frames) that depend on not only the previously displayed I- or P-frames, but also the *next* I- or P-frames to be displayed. P-frames are useful when only a small part of the picture changes between frames, for example, in a clip of a talking head. B-frames are useful when picture data is needed for the current frame is available from later frames in the clip, e.g., in a clip where a camera pans across a landscape or background scenery flows past a moving vehicle.

An H.264 stream that is encoded using P- and B-frames is substantially smaller at the same quality level than a stream encoded using only I-frames. Unfortunately for video players, using inter-frame compression complicates seeking, high-speed playback, and other non-linear operations because frames are no longer independent and instead must be considered in the context of other frames. For example, a client that seeks to a P- or B-frame and displays only that frame without fetching other frames in its context will either not be able to decode the frame or decode a distorted image. Moreover, in codecs like H.264 with bi-predictive frames, the order in which frames are decoded is decoupled from the order in which frames are displayed, and the container must ensure that the decoder gets all the data it needs (including out-of-order frames) in order to decode the current frame. In other words, a container format contains the raw encoded streams in "decode order" rather than display or "presentation order".

Frames in a ChunkStream backbone are always in presentation order. ChunkStream uses presentation order because each lane in a stream may be encoded with different parameters or even different codecs, potentially forcing each lane to have a different decode order. To help clients determine the frame decode order, ChunkStream augments the FrameData

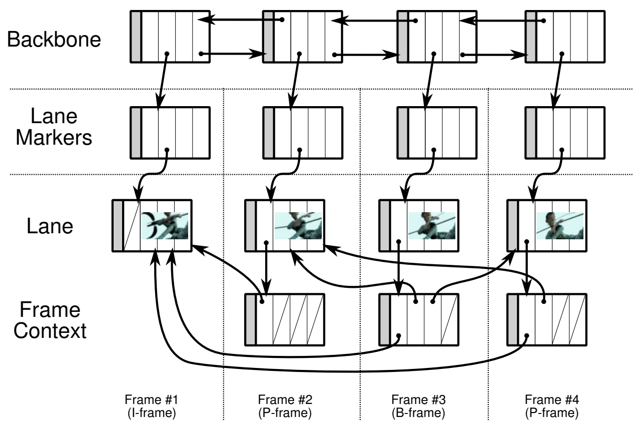


Figure 5.6: FrameContext chunks allow inter-frame compression by exposing the dependencies of a particular frame. The first slot in the FrameContext chunk always points to the I-frame that serves as the foundation of the dependent group of pictures and subsequent slots point to frames in the dependency chain between the I-frame and the current frame in the required decode order.

chunks that make up each lane with FrameContext chunks that specify the dependencies of each frame.

Each FrameContext chunk contains a link to each FrameData chunk that the frame depends on, one link per chunk slot, in the order that the frames must be decoded. FrameContext chunks contain the full context for each frame, so that the frame can be decoded without consulting any other frame's FrameContext chunks. As a consequence, the first slot of a FrameContext chunk always points to the previous I-frame in presentation order.

For example, Figure 5.6 shows a portion of an H.264-encoded video clip using inter-frame compression. Since I-frames can be decoded independently, frame 1 has no FrameContext chunk. Frame 2 is a P-frame, and as such, depends on frame 1. Frame 2, therefore, has a FrameContext chunk that specifies that frame 1 must be decoded before frame 2 can be decoded. Similarly, frame 4 has a FrameContext chunk that specifies that frame 2, and as a consequence, frame 1 must be decoded before it can be decoded[1]. Finally, frame 3 is a B-frame and as such depends on both frame 2 and frame 4, and by dependency, frame 1, so its FrameContext chunk lists frames 1, 2, and 4.

[1]In order to prevent circular references, H.264 does not allow P-frames to depend on B-frames, but only on previous P- or I-frames. As such, frame 4 cannot depend on frame 3.

5.3.2 Multimedia and Parallel Streams

So far, this thesis has only concentrated only on video streams within the ChunkStream data structures. However, most "videos" are multi-media and contain more than just video streams: a typical video file also normally contains at least one audio stream and occasionally metadata streams like subtitles. These additional streams compliment the original video and should be played along with the chosen video stream.

More generally, each of the sub-streams of a multimedia stream may be a part of a *parallel stream*. ChunkStream represents parallel streams by allowing LaneMarker chunks to contain lanes from multiple semantic streams. Recall that each lane of a LaneMarker chunk contains a link to a StreamDescription chunk with a stream identifier as well as a link to the actual data in that lane. ChunkStream clients use the stream identifier slot of StreamDescription chunks to determine which lanes are alternate versions of the same stream (two or more lanes have identical stream identifiers) and which lanes are parallel streams (two lanes have different stream identifiers).

Chapter 6

Chunk-based Optimization

One of the promises of the Chunk Model is that it enables optimization techniques using the structure exposed by chunks. This chapter details two optimization techniques, server-side paths and shape-based pre-fetching. Server-side paths leverages application-specific knowledge to skip the transmission of "infrastructure chunks" between Chunk Peers. Shape-based pre-fetching, on the other hand, is an application-generic technique that builds a model of the paths an application uses in chunk graphs and then uses that model to pre-fetch chunks that the application is likely to use.

While these techniques apply to all chunk-based data structures, this chapter explains and evaluates them in terms of the ChunkStream data structure, since ChunkStream's behaviors are more easily understood than those of arbitrary applications.

6.1 Experimental Setup

All of the tests in this chapter use the first minute of *Elephants Dream* [59] as the source video. The tests use *Elephants Dream* for its permissive Creative Commons Attribution license and the availability of its high-definition sources. The tests concentrate solely on video streaming performance; the audio tracks of *Elephants Dream* are stripped from all files transferred in the benchmarks. For ChunkStream-based tests, the *Elephants Dream* clip is compiled into a ChunkStream data structure consisting of two lanes—a high-quality lane and a low-quality lane. The ChunkStream player always chooses the high-quality lane for playback. All chunks in this section consist of 64 slots of 64 bytes each (4 KB in total size).

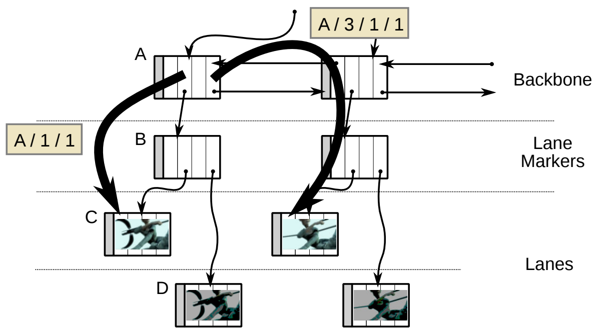


Figure 6.1: Clients using server-side path de-referencing may skip over LaneMarkers if they know what lane they want to use.

6.2 Server-side Paths

In lines 8 and 9 of the ChunkStream playback algorithm in Listing 2.1, clients fetch the LaneMarker chunk and use it to determine which lane to play. If a client has determined that a particular lane of a stream meets its requirements, it will always follow the same general path from the backbone through the LaneMarkers to the underlying video frames.

Since the client does not need the intermediate LaneMarker, except to use it to follow links to FrameData chunks, it is possible lower request overheads by giving the ChunkStream server a path to de-reference locally and send the client only the terminal chunk of the path. Figure 6.1 shows an example where the client has chosen to read the first lane of the video stream. Rather than requesting chunk A, then B, then C, the client may request that the server de-reference the slot 1 in chunk A, and then de-reference slot 1 in chunk B, and only return C, saving the transfer of chunks A and B.

Server-side path de-referencing is beneficial because it has the potential to save both bandwidth and network round-trips. To quantify the benefits of server-side path de-referencing, this section details a benchmark comparing ChunkStream to two typical video dissemination technologies: HTTP downloading and HTTP Live Streaming [81], Apple's pseudo-streaming format for iOS devices. In the benchmark, clients play the *Elephants Dream* clip from start to finish using an instrumented version of Python's standard library that captures the data transferred by each client and makes it available for analysis.

Figure 6.2 shows the total amount of data transferred using ChunkStream, HTTP download, and HTTP Live Streaming. The data transferred falls into four categories. The first

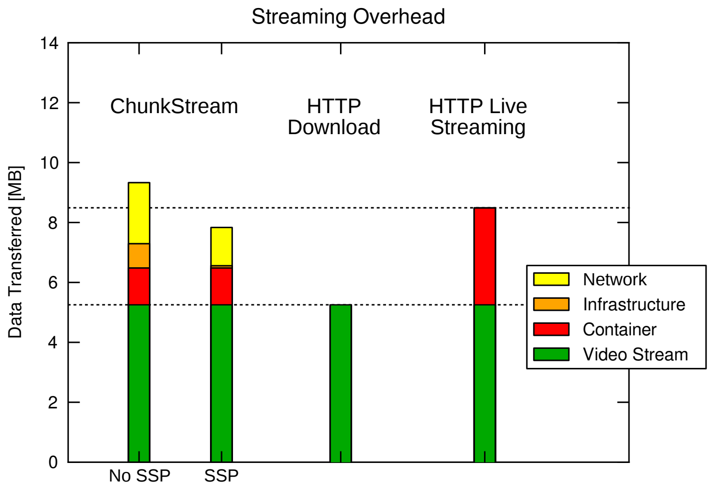


Figure 6.2: Data transferred streaming a video using ChunkStream, HTTP downloading, and HTTP Live Streaming.

category, “Video Stream”, represents the raw video codec data. Next, the “Container” category represents overheads due to the container format, ether MPEG-TS for HTTP Live Streaming, or the overheads of Frame Data chunks in ChunkStream. The “Infrastructure” category represents bytes dedicated to infrastructure concerns, such as playlists in HTTP Live Streaming or IndexTree, backbone, and LaneMarker chunks in ChunkStream. Finally, the “Network” category represents bytes that are solely due to the streaming system’s network overheads, e.g. the Chunk Exchange protocol for ChunkStream or HTTP requests and response headers for HTTP-based protocols.

The ChunkStream bars in Figure 6.2 shows network transfers with and without server-side path de-referencing optimizations turned on. When enabled, ChunkStream uses server-side path de-referencing to avoid reading LaneMarker chunks. With both caching and server-side path de-referencing enabled, infrastructure chunk overheads weigh in at about 40 KB, negligible compared to the size of the video.

HTTP Download is the best case scenario since the downloaded file is simply a small MP4 wrapper around the raw H.264 stream. Unfortunately, a file in such a format typically cannot be viewed until it is completely downloaded. HTTP Live Streaming uses MPEG-TS as its container format. MPEG-TS is designed for real-time playback, enabling files to be played during download. Unfortunately, the method that MPEG-TS uses for progressive playback leads to a 20–25% overhead compared to the raw video. In the optimized case with server-side path de-referencing enabled, ChunkStream carries 15% overhead compared

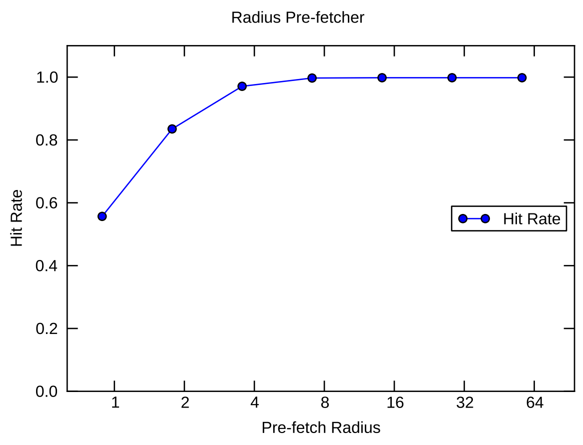


Figure 6.3: Radius Pre-fetching Performance. Note that the independent variable is plotted on a log scale.

to the raw video, which is better than HTTP Live Streaming and acceptable for consumer applications.

6.3 Chunk Graph Pre-fetching

The rest of this chapter outlines pre-fetching techniques that use the chunk graph to predict what chunks will be needed. In general-purpose architectures, there are three kinds of pre-fetching schemes. Address-based pre-fetchers observe the sequence of addresses a program accesses and attempts to predict future values [76]. Software-based methods require cooperation of a compiler to add pre-fetching instructions that the processor acts upon [20]. Finally, thread-based pre-fetchers speculatively execute threads of computation without waiting for confirmation from the memory system, allowing them predict addresses based on the actual program [65,72]. Rather than pre-fetching based on addresses, which have no semantic value in the Chunk Model, the pre-fetchers in this section try to predict which paths in the chunk graph will be used and then pre-fetch those paths. In this section, a get(id) is considered to be a hit if the chunk with the given ID is resident in the node when the application calls get() so that the get() call can return immediately without blocking.

The simplest pre-fetching algorithm is one that pre-fetches all chunks a certain radius away from chunks copied to a node. As shown in Figure 6.3, radius-based pre-fetching is effective, with a near-100% hit rate at large radii. Unfortunately, the high hit rate comes at the cost of downloading many chunks that are never used. Table 6.1 illustrates the problem.

Radius	Hits	Misses	Unused	Total Fetched	Hit Rate	Unused Fraction
1	2859	2276	2744	7879	0.557	0.348
2	4288	847	4486	9621	0.835	0.466
4	4985	150	4769	9904	0.971	0.482
8	5120	15	4882	10017	0.997	0.487
16	5125	10	4882	10017	0.998	0.487
32	5125	10	4882	10017	0.998	0.487
64	5125	10	4882	10017	0.998	0.487

Table 6.1: Table of raw Radius Pre-fetch performance values.

Source Type	Slot	Destination Type	Probability
IndexTree	0	Backbone	0.1429
		IndexTree	0.8571
Backbone	1	LaneMarker	1.0000
	3	LaneMarker	1.0000
		...	
LaneMarker	1	StreamDescription	1.0000
	2	FrameData	1.0000
FrameData	31	FrameData	1.0000

Table 6.2: Shape Table for *Elephants Dream*. The backbone portion of the table is truncated since every link in the Backbone is taken.

The fraction of unused chunks fetched by the pre-fetcher starts at around 35% for $r = 1$ and tops out at nearly 50%. At the larger radii, the pre-fetcher downloads both streams in the ChunkStream data structure even though the player only requests one of them.

A better algorithm is one that takes into account the links that an application de-references and uses that information to determine what paths to pre-fetch rather than blindly fetching everything a given distance away. The Chunk Platform's Shape Pre-fetcher does exactly this.

The Shape Pre-fetcher builds a model of the paths that an application takes through a data structure by instrumenting the Chunk Store to record what links are de-referenced from each chunk and the types of the chunks de-referenced through those links. Then it aggregates this information to construct a Shape Table mapping chunk types to the probability of taking a given slot and the probable type after de-referencing that slot. Table 6.2 illustrates the shape table generated while playing the *Elephants Dream* video. Note

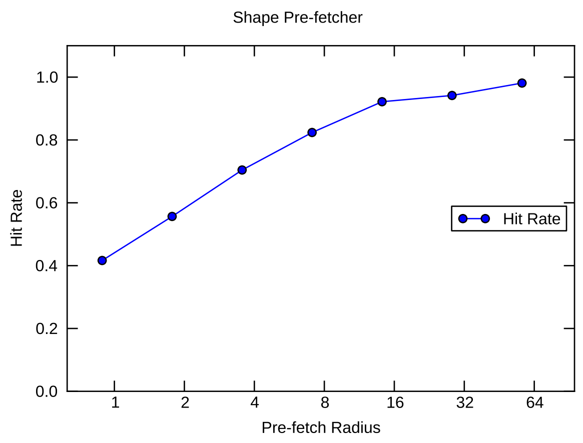


Figure 6.4: Shape Pre-fetching Performance. Note that the independent variable is plotted on a log scale.

that the table abstracts the link structure and inter-connections of the ChunkStream data structure.

The Shape Pre-fetcher uses the Chunk Platform's run-time hooks to determine which chunk slots are de-referenced. To do so, the Shape Pre-fetcher keeps a short list of chunks for which the application has called get(). When the application get()s another chunk C, the Shape Pre-fetcher checks to see if any of its short list of chunks points to C, and if so, assumes that the application followed the link from that chunk to C and updates the Shape Table accordingly.

Using the Shape Table, the Shape Pre-fetcher makes a list of which paths are most likely to be taken from a starting chunk out to a certain radius, r. The $r = 1$ case is easy: given the type of a source chunk, the pre-fetcher fetches all links whose probability are above a given threshold. The $r > 1$ case involves recursion on the Shape Table: given a starting chunk, the pre-fetcher zig-zags through the Shape Table from source chunk type to determine what is the likely destination type and probability, then uses the likely destination types as the source types for the $r - 1$ case. Once the Shape Pre-fetcher has compiled the likely paths, it starts a background thread to pre-fetch those chunks.

Figure 6.4 shows the performance of the shape pre-fetcher. Like the naïve Radius Pre-fetcher, the Shape Pre-fetcher is able to achieve a high hit rate with a large enough pre-fetch radius. As Table 6.3 shows, it does so while only downloading a single unused chunk[1].

[1]The unused chunk is downloaded when the node first discovers that slot 0 of IndexTree chunks may point to Backbone chunks in addition to IndexTree chunks.

Radius	Hits	Misses	Unused	Total Fetched	Hit Rate	Unused Fraction
1	2138	2997	1	5136	0.416	0.000
2	2858	2277	1	5136	0.557	0.000
4	3617	1518	1	5136	0.704	0.000
8	4230	905	1	5136	0.824	0.000
16	4733	402	1	5136	0.922	0.000
32	4835	300	1	5136	0.942	0.000
64	5038	97	1	5136	0.981	0.000

Table 6.3: Table of raw Shape Pre-fetch performance values.

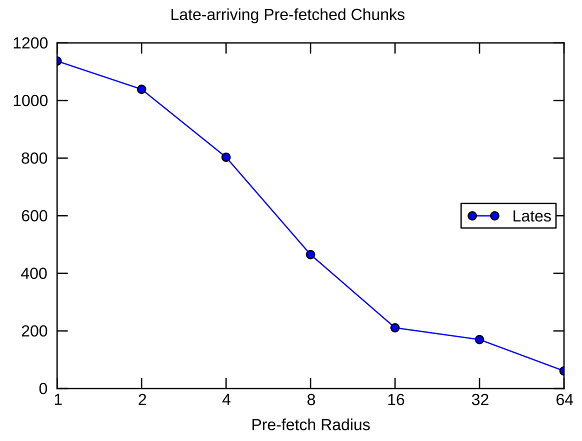


Figure 6.5: Late-arriving Pre-fetched Chunks. Note that the independent variable is plotted on a log scale.

In other words, the Shape Pre-fetcher achieves a nearly 100% accurate prediction rate. However, such a prediction rate raises a quandary: if the Shape Pre-fetcher can predict what chunks is needs, even for small radii, why isn't the hit rate equally high for all radii? The answer lies in Figure 6.5, which plots the number of "late" chunks. A late chunk is one that the pre-fetcher started to pre-fetch, but did not complete fetching, e.g., due to network or Chunk Exchange Protocol delays, when the ChunkStream video player ran its get() call. For small radii, the Shape Pre-fetcher's pre-fetch requests barely run faster than the rate at which the application calls get(). Both the application and the pre-fetcher are essentially I/O-bound. However, at larger radii the Shape Pre-fetcher is able to get ahead of the ChunkStream player when the player is CPU-bound decoding frames, ensuring that chunks are resident when the video player later requests them.

A downside to using high radius values is that in environments where there is read-write contention for chunks, e.g., SCVM threads working on the same data structures, pre-fetching may cause extra coherence messages as pre-fetchers read data for speed while writers invalidate the pre-fetched data before it is used. As such, pre-fetchers are only turned on when there is no read-write contention.

Chapter 7

Related Work

The Chunk Model and Chunk Platform draws from a wealth of related work, spanning from experimental architectures, operating systems, and mobile systems all the way up to high-level video streaming protocols and economic models for the cloud.

7.1 Architectures

This thesis is heavily influenced by a series of experimental architectures from the late 1970's and 1980's.

The idea of Reference Trees and their many uses for managing objects comes from Halstead's doctoral dissertation [47]. In particular, the Chunk Platform's consistency and garbage collection strategies are translations of Halstead's strategies to modern computing substrates. Halstead uses Reference Trees differently than we do: Halstead's Reference Trees protocols provide the functionality of the Chunk Platform's Channel layer while independent, higher-level protocols manage object copies and object garbage collection. In contrast, the Chunk Platform's Chunk Exchange Protocol is an integrated protocol that handles the Reference Tree network, chunk consistency, and garbage collection in a single finite state machine. Our approach requires more state to be kept in Reference Trees compared to Halstead's approach, but at the same time provides a more comprehensive abstraction.

The MuNet [48] machine and corresponding operating environment allowed a computation to span multiple processors and gradually migrate between them. MuNet inspired SCVM's migration techniques.

The $\mathcal{L}$ project [71] outlines a chunk memory system nearly identical to the Chunk Model described in this thesis, but with three critical differences. First, $\mathcal{L}$ is limited to a fixed topology of nodes, while the Chunk Platform allows fluid expansion and contraction of computation nodes. Second, the Chunk Model's chunks are network-accessible, while $\mathcal{L}$'s chunks work only in the context of a single machine. Lastly, $\mathcal{L}$ uses chunks as the basis for a new computer architecture, while the Chunk Platform uses chunks as an abstraction above already existing architectures. These three extensions enable the Chunk Model described in this thesis to work on the full scale of computers from embedded machines to massively multi-core machines to clusters of machines.

Ayers' $\mathcal{M}$ [9] provides a memory manager for $\mathcal{L}$'s chunks. $\mathcal{M}$ provides a single address space garbage collector as well as techniques for compacting chunks within hardware virtual memory pages. Many of the techniques in $\mathcal{M}$ can be used in a high-performance implementation of the Chunk Runtime.

A chunk-based system may be able to use optimizations developed for Non-Uniform Memory Architectures (NUMA). For example, Bolosky et al.'s NUMA kernel [16] uses VM pages as the unit of sharing and replication. Unfortunately, VM pages are prone to "false sharing" of different objects on the same VM page. The Chunk Model may suffer from the same problem if a compiler puts two objects in the same chunk. Fortunately, Granston et al. [45] argue that the compiler may be able to reduce false sharing by separating objects into different pages. Chilimbli et al. [23, 24] show that the order of fields in a data structure may help cache performance; a chunk compiler may re-order slots in a chunk to increase locality of reference.

7.2 Object Systems and Garbage Collection

The first systems to exploit graph structure of objects and references were the garbage collection algorithms. Rather than summarize the long history of garbage collection, this section will briefly outline the key papers that influenced our design of the Chunk Platform's garbage collector.

Traditionally, there are two main ways to collect garbage, either reference counting or tracing. Collectors for LISP introduced tracing and "stop the world" garbage collection [33, 68]. As address spaces grew, traditional tracing garbage collection became too slow. Bishop [15] created an algorithm that divided memory into independently-collectable "areas" to reduce garbage collection time. Baker [11] introduced a garbage collector that (1) bound the costs of garbage collection and (2) spread the costs of garbage collection across all memory operations, thus removing "long pauses" in the "stop the world" garbage collectors, enabling garbage collected systems to be used in pseudo-real-time systems. Later, Hudson et al. [55] introduced a generational garbage collection algorithm based on the observation that new objects are likely to die, and need to be garbage collected, more often than older objects. Their "train and car" algorithm divides the address spaces into independent areas based on the age of objects and then uses a Baker-like real-time algorithm to garbage collect each area. New areas are garbage collected more frequently than areas containing older objects. Bacon et al. [10], motivated by the observation that all high-performance garbage collection algorithms share characteristics of both reference counting and tracing, unified reference counting and tracing as dual algorithms that operate on dead object graphs (reference counting) or live object graphs (tracing). A chunk-based memory may be able to make use of all of these algorithms for the node-local garbage collector.

More recently, Hirzel et al. [53, 54] built a garbage collector that partition the object graph based on connectivity, rather than on age. They find that objects that are close to each other in the object graph (either through direct or transitive relationships) share many characteristics like lifetime or deathtime and can be more effectively garbage collected when garbage collected together. Hirzel's work provides reinforces the hypothesis that object connectivity may provide useful optimization hints.

There are a wide variety of distributed resource reclamation schemes, ranging from distributed versions of sequential algorithms, like Lieberman and Hewitt's extension [63] of Bishop's algorithm, to special-purpose distributed schemes. Abdullahi and Ringwood [5] provide a survey the field of distributed garbage collection. The Chunk Platform's garbage collection Chunk State bits are influenced by Dijkstra et al.'s use of graph coloring in the on-the-fly garbage collector [31]. Like the Chunk Platform's Reference Trees, SSP chains [87] enable decentralized resource management. Unlike Reference Trees, SSP chains can only be used for reference counting and as such, cannot collect reference loops.

7.3 Operating Systems

One of the perennial hot topics in operating system design for the past few decades has been scaling to bigger and more powerful machines; this thesis continues the trend. The Tornado [39] shared-memory multi-processor operating system aims to scale by leveraging locality and minimizing both intentional and false sharing. Tornado does so by partitioning operating system objects into "clustered" objects that may replicated across cores. Chunks are a natural extension of clustered objects in Tornado. More recently, Corey [17] provides three new mechanisms—address ranges, kernel cores, and shares—that allow applications to control what operating system structures are shared on their behalf. Like two threads in a chunk-based system, two threads in Corey only share what they need to share; everything else is private to the individual thread. On clusters, Cellular Disco [44] uses clusters of virtual machines to adapt commodity operating systems to large-scale NUMA machines. In contrast, we argue for a fundamental re-thinking of the structure of commodity operating systems around managing chunks.

In the Chunk Model, chunks serve the purpose that virtual memory pages do for typical operating system kernels, namely that they abstract resource allocation and placement. The virtual memory system in the Mach microkernel [95] allows memory objects, like chunks, to be mapped dynamically by applications. Unlike chunks, however, Mach's memory objects are unstructured and of arbitrary size, limiting the analysis that may be performed on them. Alternatively, the Barrelfish multikernel [13] uses information from explicit message passing to optimize communication, much as it is possible optimize memory allocation with chunks.

Internet-scale computing have lead to a resurgence in work on massively data-parallel problems. Google's MapReduce [29] structures computations into a "map" stage that transforms data and a "reduce" stage that gathers data into sets. Microsoft's Dryad and DryadLINQ [57,96] provide a more generic cluster programming system based on data-flow graphs comprised of single-threaded computation nodes connected by communication channels. The Dryad family of projects is notable for its graph-based techniques that allow a computation to be optimized at run-time simply by modifying the structure of the graph. Similar optimizations may apply to the chunk graph.

In large-scale mutli-processing systems, there is an opportunity to make use of "space-sharing" of hardware resources rather than just "time-sharing". The fos [90] factored operating system for multi-core systems treats cores as an abundant resource that should be allocated to particular problems. fos replaces the scheduler with a layout algorithm that allocates applications and OS services to their own dedicated cores. In order for the layout algorithm to work, fos requires applications to be divided into very finely-grained structured mini-servers. The chunk abstraction compliments the structural requirements that fos imposes because chunks explicitly expose the seams in applications and data structures.

7.4 Code Offload and Migration

Over the past twenty years, many projects have explored how to balance, offload, and migrate code among disparate hardware resources. Adaptive mobile systems, like Odyssey [74], Puppeteer [28], and Chroma [12] outline the various ways an application may be decomposed in a client/server system. Building upon such systems, Flinn et al. propose [36] methods for choosing when to offload code. Recent projects like MAUI [27] and CloneCloud [25] concentrate on offloading code from smartphones to cloud servers for execution speed. Yang et al. [94] analyze CloneCloud's object graph to reduce the amount of state that must be transferred during migration. ThinkAir [58] provides a framework for dynamically offloading parallel and divide-and-conquer parallel algorithms to the cloud. In contrast to these architecture-specific code offload systems, SCVM and the Chunk Platform enables a simple, yet generic, form of code offloading.

Fuggetta et al. [38] survey the field of code mobility and classifies code migration systems by the strength of their mobility, the types of resource binding allowed, and the particular software architecture that the code migration system needs. According to Fuggetta's taxonomy, SCVM provides a "code on demand" strong mobility system.

SCVM may make use of cloudlets [84] to offload computations to local compute resources rather than directly to the cloud. SCVM's data structures are much lighter-weight than proposed cloudlet implementation of copying virtual machines between mobile nodes and cloudlet nodes [92].

7.5 Pre-fetching

Most existing pre-fetching systems require pre-computed hints to determine how and what to fetch ahead of time. For example, hoarding in the SPREE [60] mobile object system uses a compiler pass to statically determine the “shape” of the objects used (e.g., the object fields accessed in a program, compared to all of the fields available). SPREE sends the current program counter and a root object to a server, which responds with the objects that the client needs to hoard. Transparent Informed Prefetching [83] uses high-level disclosure of application actions to feed its pre-fetcher. In contrast, the Chunk Platform makes use of the run-time chunk graph to determine what to pre-fetch.

7.6 Tasklet Economic Models

Tasklets provide an alternative way of consuming and paying for computing resources and, as such, can make use of the multitude of studies about cloud computing economic models.

One of the refreshing aspects of cloud computing, in contrast to privately-run data centers, is that operational costs are well-known, documented, and studied. For example, the CloudCmp Project [62] analyzes four different cloud providers in an attempt to guide consumers to the correct provider. Cloud auto-scaling [66] enables application operators automatically expand and contract cloud resources depending on external demand.

Goiri et al. [41] derive profit equations for cloud providers that take into account fixed private cloud resources (that can be shut down or “insourced”/rented to others) and public cloud resources used at a specific cost rate. Given certain assumptions on power and costs, Goiri and co-authors find it better to under-provision fixed resources, use the cloud for bursts, and then insource when the fixed cluster of nodes is not busy. Briscoe and Marinos argue for a Community Cloud [18] made out of P2P nodes to avoid “necessary evils” like vendor lock-in, cloud downtime, and privacy problems. Their work includes an idea of “community currencies” where nodes trade resources in terms of a fungible currency. A node may run a surplus, which it can then spend against nodes that run a deficit.

Durkee [32] argues that while the competition between cloud providers may reduce the cost of cloud computing, cloud computing will never be zero-cost. Cloud vendors operate in a environment of perfect competition (like cellphone vendors and airlines), so they have to make their profit by obscuring details (e.g., performance or the guarantees of service-level agreements) or costs (e.g., incoming bandwidth costs). Durkee makes the point that enterprise systems need more reliability and performance guarantees, and predicts that we will likely end up with a Cloud 2.0 that gives more value, albeit at a higher unit cost. Tasklets may be seen as one step towards a Cloud 2.0 charging model.

Mesos [52] enables sharing of data center resources among different frameworks (e.g., MPI, Dryad, MapReduce, or Hadoop). Mesos works by offering each toolkit resources and incentivizes the framework to accept only the resources it needs. Our work may benefit from the incentive structures that Mesos introduces.

Finally, Google App Engine and Amazon EC2 are expanding offerings from the pure models mentioned in Section 5.2. EC2 Spot Instances [7] enable users to bid on excess capacity that would otherwise be wasted by Amazon, providing a way of lowering the cost of EC2 virtual machines. Similarly, App Engine offers Task Queues [43] for long running tasks that do not fit in a request/response format. Both offerings speak to the need for additional cloud computing models, of which Tasklets is one alternative.

7.7 Persistent Programming Systems

Persistent programming systems, of which Cahill [19] provides a large survey, provide a hybrid model that offers the persistence of storage systems and the computation model of object-oriented programming languages. The abstractions provided by persistent programming systems resemble our chunk abstraction without the size restrictions. For example, the Mneme object store [73] is built upon object vectors that contain either data or object references and are stored in files specified by the programmer. To keep object addresses short (and allow local applications to use purely local names), an object may only refer to other objects within a particular file. In order to refer to objects external to the file, a Mneme object points to a “forwarder object” within the file that is treated specially by the Mneme runtime. More recently, InterWeaves [89] provides an similar object model based on Internet URLs. The Chunk Model extends the persistence goals of these systems with notions of locality and hardware resource management.

7.8 Locality-aware Re-structuring

Compiler writers have tried to take advantage of locality to improve program performance. For example, Gloy et al. [40] outline an algorithm for producing a graph of procedure calls weighted by how execution may alternate between two procedures. His group used the graph to place code to avoid cache conflicts. The chunk graph may be annotated with Gloy's temporal ordering information to help resource allocation.

Others have worked on cache-aware data placement. Calder et al. [21] introduced Cache-conscious Data Placement (CCDP), a profile- and compiler-driven technique for placing data within cache blocks. Chilimbi et al. [23,24] investigated a four techniques for decreasing cache conflicts. One technique provides a new memory allocator, ccmalloc, that takes pointer as an additional argument and uses that pointer as a hint of where to place the newly allocated memory, e.g., place a child node in a tree close to its parent. In many ways ccmalloc is a step towards the Chunk Model where explicit links denote locality.

Static pointer analysis [51] at compile time promises to aid optimization. However, static pointer analysis runs into scalability and scope issues: pointer analysis only works well when it can run over the entire program, including all of the libraries that the program may use. As such, analysis problems quickly become intractably large.

7.9 Video Streaming

Video streaming solutions fit into three general categories: streaming, downloading, and pseudo-streaming [46]. Two common streaming solutions are IETF's RTP/RTSP suite [85,86] and Adobe's RTMP [4]. RTP/RTSP uses a combination of specially "hinted" files, TCP control streams, and UDP data streams to give users frame-accurate playback over both live and pre-recorded streams. RTMP is a specialized protocol for streaming Flash-based audio and video over TCP. Unlike RTP/RTSP, RTMP multiplexes a single TCP connection, allowing it to more easily pass through firewalls and NATs at the cost of the complexity of multiplexing and prioritizing sub-streams within the TCP connection. Clients have some control over the stream and may seek to particular timestamps.

On the other hand, many clients "stream" video by downloading a complete video file over HTTP. HTTP downloading is simple, but does not allow efficient seeking in content that has not yet been downloaded, nor can it adapt to varying bandwidth constraints. Pseudo-streaming is an extension of the download model that allows clients to view content as it is downloaded. Recently, Pantos's work on HTTP Live Streaming [81] extends the HTTP pseudo-streaming model by chunking long streams into smaller files that are individually downloaded. A streaming client first downloads a "playlist" that contains the list of video segments and how long each segment lasts. The client then streams each segment individually. The HTTP Live Streaming playlist may contain "variant" streams, allowing a client to switch to a, e.g., lower bandwidth, stream as conditions warrant. Seeking is still awkward, as the client must download an entire segment before seeking is possible.

Of the three categories, streaming is the most bandwidth-efficient, but pseudo-streaming and downloading are the most widely implemented, likely because of implementation simplicity [46].

Chapter 8

Summary and Future Work

This thesis starts with two observations about recent trends in computing. The first observation is that the traditional machine abstraction of strings of assembly code running in a flat virtual memory hides important details about the machine from programs and details about programs from the machine. While hiding and abstracting details can be beneficial, it can also be harmful if the abstraction no longer fits the problem at hand. This leads to the second observation: modern computing substrates have new features and properties that do not fit in the traditional computing abstraction. Modern computing substrates come with their own machine model extensions because the traditional computing model does not provide enough information about the internal structures of programs and the machines that run them to build run-time systems to properly support applications on the substrate. Programmers that wish to use modern computing substrates must use platform-specific frameworks to manage these new hardware resources. Rather than learning one machine model, programmers must now master many machines models, each its own unique extensions, strengths, and caveats.

The goal of this thesis is to test the hypothesis that preserving and exposing structural information at the machine level will make it easier to build generic system-level support for wide classes of applications running on a variety of modern computing substrates. In order to evaluate that hypothesis, we formalize a structured memory model, the Chunk Model, and build the Chunk Platform, an implementation of the Chunk Model. The Chunk Model replaces the traditional flat memory with structure-preserving graphs of fixed-size chunks. The Chunk Model, since it is just a structured generalization of the unstructured von Neumann memory model, is both application-generic and platform-generic, giving us exactly the foundation we need to test our hypothesis.

We use the Chunk Platform to test the feasibility of building a real system based on the Chunk Model. The Chunk Platform demonstrates:

- a chunk-based application programming interface that captures application structure in graphs of chunks,
- a wire format for sharing graphs of chunks between independent nodes of a computing substrate,
- the Chunk Exchange Protocol, a distributed network protocol that uses Reference Trees to implement a programmer-friendly sequentially consistent memory model for shared graphs of chunks,
- a distributed garbage collection algorithm of chunk graphs that can collect cycles distributed across independent nodes,
- optimization techniques that use the chunk graph to pre-fetch or omit data as needed by applications,
- SCVM, a chunk-based virtual machine that captures the basic block structure of programs as chunk structure in graphs, and
- a reference compiler that targets SCVM and makes use of the advantages of the Chunk Model, yet provides a familiar programming language and programming environment that hide the details of chunks from the programmer.

We evaluate the Chunk Platform by building a variety of sample applications in both traditional areas like scientific computing and video streaming, as well as new areas such cloud computing and task migration.

Our experience implementing the Chunk Platform and the applications that use it testify to the claim that the Chunk Model is a plausible way of building a structured computing system that provides useful functionality for applications and run-time layers. For those who want to experiment with the Chunk Model for themselves, source code is available from http://o2s.csail.mit.edu/chunks under a free and open source license.

8.1 Future Work

As we developed the Chunk Model and Chunk Platform, we made several design decisions and assumptions that may bear revisiting.

8.1.1 High Performance Chunk Platform

The Chunk Platform described in this thesis is not focused on high performance. While it provides a useful vehicle for experimentation with small applications, there many ways to improve the performance of the Chunk Platform. For example, the internals of the Chunk Runtime use implementation-convenient, but run-time inefficient, objects and data structures to represent the Channel Peer and Chunk State objects in the Chunk Exchange layer. A re-write of the Chunk Runtime that pays careful attention to software efficiency could pay dividends in building a Chunk Platform that can be used to benchmark the generic Chunk Model against native substrate-specific programming frameworks.

8.1.2 Reference Tree Reliability

The Chunk Exchange Protocol assumes that substrate networks are reliable in order to provide its correctness guarantees. In the current iteration of the Chunk Exchange Protocol, the loss of a node or a channel could lead to the partitioning of Reference Trees at best and at worst lead to loss of data, if, for example, the node that died held the sole valid copy of a chunk. More complex versions of the Chunk Exchange Protocol may allow the Chunk Platform to mitigate problems due to faulty nodes. For example, to heal partitioned Reference Trees, the Chunk Runtimes on nodes around the partition could flood the substrate network with discovery messages in an attempt to find the other branches of the Reference Tree. To solve the problem of lost data, future versions of the Chunk Exchange Protocol could choose to keep invalid shadow copies of chunks around so that if the loss of the sole copy of the chunk occurs, the system may roll back to an older version of the chunk.

8.1.3 Migration of Computation

The Chunk Platform optimizes chunk placement by using pre-fetchers that can predict what chunks applications will need. However, as alluded to in the discussion of volumes of influence in Section 2.3.2 and the implementation of the PhotoBoss web application in

Section 5.1.3, another potential way of achieving high-performing chunk systems is to move entire computations so that threads are close to the resources that they require.

A key challenge is automating migration without requiring the use of programmer-provided hints or the help of a centralized component that monitors global knowledge of the entire program, since neither programmer hints nor centralized components scale well. One promising approach to automatic migration is to expand the distributed representation of Reference Trees to include a measure of how long each Reference Tree is, how far messages must travel in the Reference Tree, and the relative distribution of hostage nodes. The Chunk Runtime on each node could then monitor the new Reference Tree statistics and attempt to swap computations with neighboring nodes to minimize one of the measures.

A side benefit of automatic migration is that it allows movable computations to cluster around immobile resources. For example, if a particular computing substrate includes heterogeneous nodes with different capabilities, computations that make use of the special features of one node may cluster around that node, enabling efficient use of those specialized resources.

8.2 Concluding Remarks

Computer science research often assumes that the von Neumann machine abstraction is the only machine model worth exploring. While making such an assumption is convenient since von Neumann machines are cheap and plentiful, doing so ignores the value of exploring alternative assumptions and models. The Chunk Model and Chunk Platform developed in this thesis represent a new architecture that generalizes the von Neumann model to solve the abstraction problems of modern computing substrates. The approach presented in this thesis is but one of many possible new structured computing models that may help us better use new machines. While researching non-traditional computing models requires more initial investment in infrastructure, as the field of computer science continues to mature, investments in alternative architectures allow us the luxury to reconsider our long-held assumptions and dream of new abstractions that transcend what we have today.

Appendix A

Reactor Transition Pseudo-code

This appendix contains pseudo-code implementations of the Reactor transition functions. The functions take as a request and a chunk ID as parameters.

Each function terminates with one of two primitives. The finish() primitive indicates that the request has been fully handled and should be removed from the Request Queue. The Reactor then moves onto the next request, if there is one. The wait() primitive indicates that the request has not been fulfilled yet. The Reactor will go to sleep until an external change wakes it up.

The transition functions may make use of two Channel layer messaging functions:

send_status(dest, msg_type, ...) Send a status message of type msg_type to the channel named by dest.

maybe_send_request(dest, msg_type, chunk_id, requester) Send a request message of type msg_type to the channel named by dest that originated from requester only if we have not already sent that message before while handling the current request.

maybe_send_request() helps suppress duplicate messages on the Reference Tree.

```
# Forward a C? request to others, being careful not to forward the
# request back to the requester.
def fc(request, chunk_id):
    for channel in channels:
        if channel.state == C or channel.state == G:
            if channel != request.return_direction:
                maybe_send_request(channel, "C?",
                                   chunk_id, requester=request.requester)
    wait()
```

Listing A.1: The FC Transition.

```
# Forward an E? request towards chunk copies, being careful not to
# forward the request back to the requester.
def fe(request, chunk_id):
    for channel in channels:
        if channel.state == C or channel.state == G:
            if channel != request.return_direction:
                maybe_send_request(channel, "E?",
                                   chunk_id, requester=request.requester)
    wait()
```

Listing A.2: The FE Transition.

```
# Request a chunk from branches of the Reference Tree that have copies
# of the chunk.
def rqc(chunk_id, request):
    for channel in channels:
        if channel.state == C or channel.state == G:
            maybe_send_request(channel, "C?", chunk_id, requester=self)
    wait()
```

Listing A.3: The RQC Transition.

```
# Evacuate all copies of the chunk in branches that have the chunk.
def rqe(request, chunk_id):
    for channel in channels:
        if channel.state == C or channel.state == G:
            maybe_send_request(channel, "E?", chunk_id, requester=self)
    wait()
```

Listing A.4: The RQE Transition.

```
# Respond with a shared copy of the chunk
def rsc(request, chunk_id):
    chunk_state = get_chunk_state(chunk_id)
    if chunk_state.M:
        # Can't share a chunk when an application holds a Modify
        # privilege on that chunk.
        wait()
    else:
        chunk = store.get(chunk_id)
        send_status(request.return_direction, "C+", chunk_id, chunk)
        finish()
```

Listing A.5: The RSC Transition.

```
# Respond to a C? request by giving up a copy of the chunk since we no
# longer need it.
def rse(request, chunk_id):
    chunk_state = get_chunk_state(chunk_id)

    if chunk_state.M or chunk_state.R:
        # Local privileges are currently being held.
        wait()
    else:
        chunk = store.get(chunk_id)
        send_status(request.return_direction, "C−", chunk_id, chunk)
        store.delete(chunk_id) # clears C and S bits
        finish()
```

Listing A.6: The RSE Transition.

```
# Make forward progress on an E? request, either by sending messages
# towards copies, or if all downstream copies have been invalidated,
# responding directly to the request.
def frse(request, chunk_id):
    if other_branches_copyless(request.return_direction):
        # All branches downstream of the request no longer have copies
        # so we can respond directly to the request.
        rse(request, chunk_id)
        finish()
    else:
        # Forward the request to branches that have copies.
        fe(request, chunk_id)
        wait()
```

Listing A.7: The FRSE Transition. The other_branches_copyless function returns False if any channel except the channel named by request.return_direction is in the C or G state (i.e., the function returns False when all downstream branches have no valid copies of the chunk).

```
# Return chunk to the locally running application with Read privileges
# as long as no other application has Modify privileges for the chunk.
def grr(request, chunk_id):
    chunk_state = get_chunk_state(chunk_id)
    if chunk_state.M:
        # Another application has modify access to the chunk
        wait()
    else:
        chunk = store.get(chunk_id)
        chunk_state.set(R) # Grant Read privilege
        return_chunk(request.requester, chunk)
        finish()
```

Listing A.8: The GRR Transition.

```
# Return chunk to the locally running application with Modify
# privileges as long as no other application has Modify privileges for
# the chunk.
def grm(request, chunk_id):
    chunk_state = get_chunk_state(chunk_id)
    if chunk_state.M or chunk_state.R:
        # Another application has privileges on the chunk. Wait until
        # they are relinquished before granting modify access.
        wait()
    else:
        chunk = store.get(chunk_id)
        chunk_state.set(M) # Grant Modify privilege
        return_chunk(request.requester, chunk)
        finish()
```

Listing A.9: The GRM Transition.

```
# Leave the Reference Tree
def gclt(request, chunk_id):
    for channel in channels:
        if channel.state == N or channel.state == C:
            send_status(channel, "RU", chunk_id)

    clear_tree_state(chunk_id)
    finish()
```

Listing A.10: The GCLT Transition.

```
# Delete the only remaining copy of the chunk
def gcd(request, chunk_id):
    clear_tree_state(chunk_id)
    store.delete(chunk_id)
    finish()
```

Listing A.11: The GCD Transition.

```
# Ask another Chunk Peer to guarantee the chunk for this Chunk Peer,
# so that this Chunk Peer can eventually leave the Reference Tree.
def gcrg(request, chunk_id):
    # If we're already guaranteeing the chunk for another Chunk Peer,
    # we must wait for that Chunk Peer to make use of it's guarantee
    # before we can proceed.
    for channel in channels:
        if channel.state == G:
            wait()

    # Find a suitable guarantor:
    for channel in channels:
        if channel.state == C or channel.state == R:
            maybe_send_request(channel, "G?" chunk_id, requester=self)
            # By our garbage collection rules, only Reference Tree
            # leaves can attempt to leave the tree, so there must be
            # exactly one channel we can ask for a guarantee.
            break

    wait()
```

Listing A.12: The GCRG Transition.

Appendix B

SCVM Specification

SVCM is a stack-based, chunk-oriented virtual machine. This makes it different in structure than most real machines, though it shares some characteristics with other virtual machines (like Java's object-oriented VM or Python's stack-based VM).

SCVM is a stack-based virtual machine. In contrast to a register-based machine that exposes registers to store ephemeral values, a stack-based machine exposes a stack of values. Instructions in a stack-based machine manipulate the stack by popping values off the stack, operating on the values, and pushing values back onto the stack.

SCVM is a chunk-oriented virtual machine. In contrast to a flat-memory machine, "system memory" is not an individually-addressable array of bytes, but rather a universe of chunks. SCVM distinguishes between scalar values and references to chunks; it is not possible to de-reference a scalar value to get a chunk.

B.1 SCVM Programming Environment

SCVM exports an environment- and closure-based computation model. In an environment-based computation model all data accessible to the computation are accessible through a linked list of "environments". Each environment is represented by an Environment chunk. Programs find, read, and write data by finding the appropriate slots in Environment chunks. In a closure-based computation model, every function is "closed" in a particular lexical environment to create a closure. The only way to apply the function is to create a new environment for the function execution and connect that new environment to the environment of the closure.

B.1.1 Threads

Every thread of computation in SCVM is represented by a Thread chunk. The thread chunk exposes two slots to the programmer:

Slot 0 Link to environment chunk

Slot 1 Link to the currently executing closure

Slot 0 provides the programmer with access to the environment, and as such, "main memory". Slot 1 points to the currently executing closure, allowing programs to easily make recursive calls.

The rest of the slots in the Thread chunk are implementation specific. In the Python implementation, the rest of the slots are:

Slot 2 Program counter link to code chunk

Slot 3 Program counter scalar code offset

Slot 4 Link to top of stack

Slot 5 Link to previous thread chunk

The Python implementation uses a new Thread chunk for each function call; other implementations need not follow this convention.

B.1.2 Environments

Environments are represented using Environment chunks. Environment chunks have the following format:

Slot 0 Link to parent environment

Slot 1 Link to symbols or empty

Slots 2–(N-1) bound variables

The first slot of the "global environment" Environment chunk is empty; all other Environment chunks must have a valid parent link. If the Environment has values that may be looked up by name, the names are defined in a chunk pointed to by slot 1. The format of the "symbols" chunk is currently undefined. The rest of the slots are bound variables, each accessed by slot number.

B.1.3 Closures and Functions

Closures are represented using Closure chunks. Closure chunks have two defined slots:

Slot 0 link to enclosing environment

Slot 1 link to available functions.

The first slot points to an Environment chunk, while the second slot points to a Function chunk containing pointers to available implementations of the closed function.

Function chunks have the form:

Slot 2i description of implementation i

Slot 2i+1 link to code chunk

The description is a scalar string. All SCVM interpreters must support SCVM bytecode with the description scvm and a link to Code chunks. SCVM interpreters may support other code types each with their own specification for how the code should be called.

Function calls are made by "applying" a closure to a set of arguments. Before the call to some closure C, the caller pushes the arguments of C on the stack in reverse order (so that the first argument is at the top of the stack), pushes the a link to the closure, then calls the function using the call instruction. When interpreting the call instruction, the machine creates a new Environment chunk E for the function call and set's E's parent to be the value of C's static environment. The machine then copies the arguments to E as the first N bound variables. The machine then creates a new Thread chunk T whose environment is E and whose closure is C. T also contains any necessary information to allow the closure to return to the caller. Finally, the machine replaces the old Thread chunk with T and starts executing C's code. When C returns, any returned values are pushed on to the stack, the caller's Thread chunk is restored, and E and T are de-referenced (allowing the Chunk Platform's garbage collector to reclaim them as necessary).

Interpreters that support non-SCVM code must use the same calling convention: arguments are pushed on the stack before the call instruction, arguments are popped off during the call instruction, and all returned values are pushed on the stack when the call instruction returns.

B.1.4 Constants

Integers in SCVM are represented as strings in Base 10. The two Boolean values are the strings True and False; any value that is not True is considered to be False.

B.2 SCVM Instructions

SCVM instructions are strings that fit inside the slot of a chunk. SCVM instructions obtain their operands from one of three places:

- From an immediate value embedded in the instruction,
- From values popped off the stack, and
- From the code chunk itself.

In general, the immediate value is a scalar value. During execution, SCVM instructions may (1) access and modify chunks linked to by the root Thread chunk and (2) modify the stack.

B.2.1 Stack Manipulation Instructions

pushs: Push Scalar

Form:	pushs VALUE
Operation:	Push VALUE onto the stack as a scalar value. *Warning:* The pushs instruction should not be used when VALUE may be nearly the size of a slot. When the size of VALUE is almost as large as the slot, or when the size of VALUE is not easily calculated, put VALUE in a slot and use pushnext.

pushe: Push Empty

Form:	pushe
Operation:	Push an empty value to the top of the stack.

pushnext: Push Next Value

Form:	pushnext
Operation:	Push the value of the slot immediately after the pushnext in the currently executing code chunk.

pop: Pop Top

Form:	pop
Operation:	Delete the value at the top of the stack.

copy: Copy Top

Form:	copy
Operation:	Copy the top of the stack so that the top two elements of the stack contain the same value.

swap: Swap Top

Form:	swap
Operation:	Swap the top two values of the stack.

B.2.2 Chunk Manipulation Instructions

alloc: Create a new chunk

Form:	alloc TYPE
Operation:	Allocate a new chunk of type TYPE. Push the id of the chunk as a link on the stack.

slot: Get value of slot

Form:	slot NUM
Operation:	Pop the top of the stack and interpret it as a link to a chunk C. Push slot NUM of C on the stack.

slot_rel: Get value of relative slot

Form:	slot_rel
Operation:	Pop the top of the stack and interpret it as a link to a chunk C. Pop the next value on the stack and interpret it as an integer NUM. Push slot NUM of C on the stack.

store: Set value of slot

Form: store NUM

Operation: Pop the top of the stack and interpret it as a link to a chunk C. Pop the next value on the stack into temporary storage T. Set slot NUM of C to be the value of T.

store_rel: Set value of relative slot

Form: store_rel

Operation: Pop the top of the stack and interpret it as a link to a chunk C. Pop the next value on the stack and interpret it as an integer NUM. Pop the next (third) value on the stack into temporary storage T. Set slot NUM of C to the value of T.

root: Get the value of a slot in the root Thread chunk

Form: root NUM

Operation: Push the value of slot NUM of the root Thread chunk on the stack.

B.2.3 Integer Instructions

mathop: Binary Math Operations

Form: OP

Operation: Pop the top of the stack to value A; pop the next value on the stack to value B, calculate A OP B, and push that value back on the stack. A and B must be scalar values that evaluate to integers. OP may be any of the following operations: add, sub, mul, or div. Division by zero will cause the interpreter to signal an error condition.

neg: Integer Negation

Form: neg

Operation: Pop the top of the stack to value A, then push the integer negation of A back on the stack.

B.2.4 Comparison Instructions

cmpop: Binary Comparison Operations

Form: OP

Operation: Pop the top of the stack to value A; pop the next value on the stack to value B, calculate A OP B, and push the resulting Boolean value to the stack. A and B must be scalar values that evaluate to integers. OP may be either ==? for equality comparison or <? for a less-than comparison.

B.2.5 Boolean Instructions

boolop: Binary Boolean Instructions

Form: OP

Operation: Pop the top of the stack to value A; pop the next value on the stack to value B, calculate A OP B, and push the resulting Boolean value to the stack. OP may be and or or.

not: Logical Negation

Form: not

Operation: Pop the top of the stack and push its Boolean negation.

B.2.6 Function Instructions

call: Apply closure to parameters

Form: call NUM_ARGS

Operation: Pop the top of the stack to get the closure C to call. Create a new Environment chunk E and set E's parent environment to the static environment of the closure.

Pop NUM_ARGS values off of the stack and store them as slots 2 through NUM_ARGS+2 in E. Update the root Thread chunk R so that slot 0 of R points to E and slot 1 of R points to C.

Store the current PC so that the return instruction functions properly. Set the next PC to be the first slot of the function pointed to by C.

return: Return from a procedure

Form:	return NUM_RVALS
Operation:	Pop the NUM_RVALS values off the top of the stack into temporary storage T; push the NUM_RVALS back on to the stack of the caller (if there is a different stack). Restore the PC to the instruction after the one set by the most recent call instruction.

system: Apply system function to arguments

Form:	system NUM_ARGS
Operation:	Pop the top of the stack to get the name of the system function to call. Pop NUM_ARGS values off of the stack and use them as the arguments to the function. Call the system function. When the function returns, push returned values back on the stack.

B.3 Warts

There are two warts in the SCVM bytecode:

- Given the slot and store class of instructions, the root instruction should return the id of the root chunk, rather than allowing only access to a slot. However, by hiding the chunk ID of the Thread chunk, the SCVM interpreter can protect against writes to the machine's own slots in the root chunk.
- slot_rel and store_rel should be implemented slot and store with no argument passed.

Appendix C

Big Jacobi Source Code

```
// See jacobi.js for the explanatory text

var NODEROWS = system.getConfig("jacobi.rows", 2);
var NODECOLUMNS = system.getConfig("jacobi.columns", 2);
var NUMNODES = NODEROWS*NODECOLUMNS;

// Make some big matrices.
var WIDTH = system.getConfig("jacobi.width", 120);
var HEIGHT = system.getConfig("jacobi.height", 120);

// Setup the A matrix with the boundary conditions
var TOP = 0;
var BOTTOM = 0;
var LEFT = 16;
var RIGHT = 0;

// Setup the B matrix as a diagonal
var DIAGONAL = 1024;

function createMatrixParallel(kernel, width, height, numNodes) {
    var matrix = [];
    var i = 0;
    var barrier = parallel.newBarrier(numNodes);
    var rowsPerNode = height / numNodes;

    for (i = 0; i < height; i = i+1) {
        matrix.push([]);
    }

    for (i = 0; i < numNodes-1; i = i+1) {
        parallel.spawn(kernel,
                            matrix, width, height,
                            rowsPerNode*i, rowsPerNode*(i+1),
                            barrier);
    }
    kernel(matrix, width, height,
           rowsPerNode*(numNodes-1), height, barrier);

    return matrix;
}

function createAMatrixKernel(matrix, width, height, rowStart, rowMax, barrier) {
    for (var i = rowStart; i < rowMax; i = i+1) {
        var row = matrix[i];
        for (var j = 0; j < width; j = j+1) {
                // Boundary conditions
                if (i == 0) {
                    row.push(TOP);
                } else if (i == (height-1)) {
                    row.push(BOTTOM);
                } else if (j == 0) {
                    row.push(LEFT);
                } else if (j == (width-1)) {
                    row.push(RIGHT);
                } else {
                    // Non-boundary conditions
                    row.push(0);
                }
            }
        }
        barrier.wait();
}

function createBMatrixKernel(matrix, width, height, rowStart, rowMax, barrier) {
        for (var i = rowStart; i < rowMax; i = i+1) {
            var row = matrix[i];
            for (var j = 0; j < width; j = j+1) {
                if (i == 0 || i == (height-1)) {
                    // Don't touch boundaries in B
                    row.push(0);
                } else if (i == j) {
                    row.push(DIAGONAL);
                } else {
                    row.push(0);
                }
            }
        }

        barrier.wait();
}

// Copy the contents of a to a new matrix.
function copyMatrixParallel(a, numNodes) {

        function kernel(matrix, width, height, rowStart, rowMax, barrier) {
            for (var i = rowStart; i < rowMax; i = i+1) {
                var row = matrix[i];
                var srcRow = a[i];
                for (var j = 0; j < width; j = j+1) {
                    row.push(srcRow[j]);
                }
            }
            barrier.wait();
        }

        var b = createMatrixParallel(kernel, a[0].length, a.length, numNodes);
        return b;
}


// Calculate \del^2 A + B = 0.  Return A.
function jacobiKernel(a, b, next, iterations, nodeParams) {

        var tmp = [];

        var rows = a.length;
        var columns = a[0].length;

        for (var iter = 0; iter < iterations; iter = iter+1) {

            // Figure out what sub-matrix this kernel instantiation should
            // operate on.  Initialization of start variables to 1 and max
            // variables with a -1 come from avoiding the boundary
            // condition cells.

            var rowStart = 0;
            var colStart = 0;
            var rowMax = 0;
            var colMax = 0;
            var rowStride = rows/nodeParams.rows;
            var colStride = columns/nodeParams.columns;

            if (nodeParams.row == 0) {
                rowStart = 1;
            } else {
                rowStart = rowStride*nodeParams.row;
            }

            if (nodeParams.row == nodeParams.rows-1) {
                rowMax = rows-1;
            } else {
                rowMax = rowStride*(nodeParams.row+1);
            }

            if (nodeParams.column == 0) {
                colStart = 1;
            } else {
                colStart = colStride*nodeParams.column;
            }

            if (nodeParams.column == nodeParams.columns-1) {
                colMax = columns-1;
            } else {
                colMax = colStride*(nodeParams.column+1);
            }

            for (var i = rowStart; i < rowMax; i = i+1) {
                for (var j = colStart; j < colMax; j = j+1) {
                    next[i][j] = (
                        (a[i-1][j] + a[i+1][j] + a[i][j-1] + a[i][j+1])/4
                            + b[i][j]
                    );
                }
            }

            // Swap a and nextA so nextA becomes a for the next round.
            tmp = next;
            next = a;
            a = tmp;

            nodeParams.barrier.wait();
        }

        return a;
}

// Start jacobi threads in parallel for each node. Return the final
// value (which is a mutated version of a).
function parallelJacobi(a, b, iterations, nodeRows, nodeColumns) {

        // Make a new barrier that knows how many threads it has to wait
        // for before it can move one.

        var barrier = parallel.newBarrier(nodeRows*nodeColumns);
        var next = copyMatrixParallel(a, nodeRows*nodeColumns);

        for (var i = 0; i < nodeRows; i = i+1) {
            for (var j = 0; j < nodeColumns; j = j+1) {

                if (i == 0 && j == 0) {
                    // We'll handle the upper right hand corner locally
```

```
                    continue;
                }

                parallel .spawn(jacobiKernel, a, b, next, iterations ,
                                {
                                    row: i ,
                                    column: j ,
                                    rows: nodeRows,
                                    columns: nodeColumns,
                                    barrier : barrier
                                });
            }
        }

        // Since we're running this code locally , we' ll also get the
        // return value locally .
        a = jacobiKernel(a, b, next, iterations ,
                    {
                        row: 0,
                        column: 0,
                        rows: nodeRows,
                        columns: nodeColumns,
                        barrier : barrier
                    });

        return a;
}

function printMatrix (m) {
        for (var i = 0; i < m.length; i = i+1) {
            for (var j = 0; j < m[0].length; j = j+1) {
                console.write(m[i ][ j ]);
                console.write(" ");
            }
            console.write("\n");
        }
}

var A = createMatrixParallel (createAMatrixKernel, WIDTH, HEIGHT, NUMNODES);
console.log("Created Matrix A");

var B = createMatrixParallel (createBMatrixKernel, WIDTH, HEIGHT, NUMNODES);
console.log("Created Matrix B");

var a = parallelJacobi (A, B, 10,
                        NODEROWS, NODECOLUMNS);

if (system.getConfig("jacobi.print", false) == 1) {
        printMatrix (a);
} else {
        console.log("Computed Jacobi");
}
```

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