

PC2L: A Parallel and Cloud Computing Library for Big Memory Applications

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PC2L: A Parallel and Cloud Computing Library for Big Memory Applications

Submitted to the
Faculty of Miami University
in partial fulfillment of
the requirements for the degree of
Master of Science
by
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Oxford, Ohio
2021

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Chapter 1

Introduction

1.1 Motivation

According to the International Data Corporation, the size of global data is expected to grow from 33 in 2018 to 175 zetabytes in 2025 as shown in Figure 1.1. [10] To put that into perspective, the variations in one human genome can be compressed in a lossless fashion to 4 megabytes of data [11], so the size of our data in 2025 will be equivalent to the digital representation of over 4 quadrillion humans.

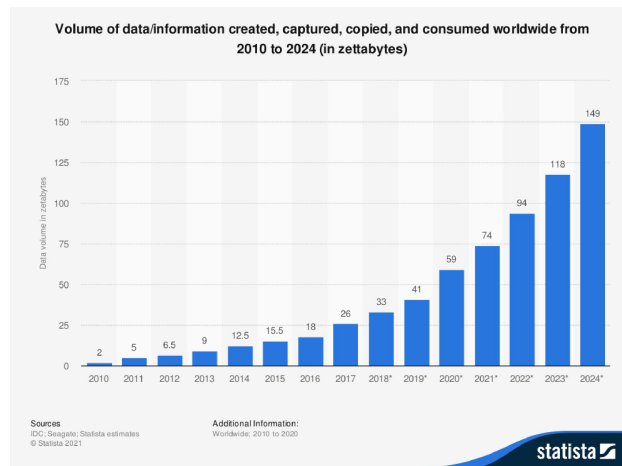


Figure 1.1: Global Data Growth through 2024. Source: International Data Corporation

Along with all of this growth in data comes a growth in the amount of memory with which applications must work. In high performance computing (HPC), we define a computing cluster as a co-located set of computers, each individually called a node, configured for accomplishing a shared task. Administrators have begun to include "big memory" nodes in these clusters which contain an above average amount of Random Access Memory (RAM) in order to address workloads that require excessive in-memory data. Prominent examples of these workloads include applications that utilize in-memory databases, graph analytics [12], and large simulations.

C++ is one of the most popular languages for distributed computing solutions, partly owing owing to the fact that it offers support for useful object-oriented abstractions in conjunction with highly optimized code. [13] While much prior work has been dedicated to creating distributed libraries in C++ in [14] [15] [16] [17] [18] [19] [20], other separate

work has attempted to improve performance on big memory applications through various optimizations [12], and still other work has been dedicated to efficiently managing distributed memory [21] [22] [23] [24] few, if any, attempts have been made to create a library of standard data structures that are designed with big memory capabilities and work loads in mind. Additionally, few general purpose distributed computing libraries are available to the public under open source distribution licenses, as many provide some sort of proprietary value add. This research will be an attempt to create such an open source distributed computing library optimized for big memory utilization, experimenting with novel implementation techniques for standard data structures and drawing from existing literature when necessary.

The main difference between PC2L and similar libraries will be in its focus on memory intensive workloads. Existing parallel and distributed libraries put more emphasis on optimizing the performance of single threads, This is perfectly fine for applications in which there is more demand for CPU operations than memory bandwidth, but focusing entirely on the performance of individual threads can paradoxically lead to worse performance when memory footprint is a program's main constraint. PC2L will also be a library that can be included in any existing distributed C++ project instead of a stand-alone dialect of C++.

1.2 Contributions

This thesis project will make the following contributions:

- an improved C++ memory allocator designed for effectively utilizing big memory
- Modular distributed data structures that can easily be inserted into existing programs with little change in code complexity
 - vector
 - unordered multi-map
 - graph
- garbage collector designed for memory hungry programs running on distributed systems

These contributions will be delivered through a portable C++ library that can run on both local computers and networked supercomputing clusters.

Chapter 2

Background & Related Work

2.1 Parallel vs. Distributed Computing

Before detailing the most prominent continuing projects in this space, it is important to draw a distinction between parallel and distributed computing. In order to do that, clear definitions for parallel and distributed computing must be provided. While this thesis project will primarily be geared toward distributed applications running in high-performance computing (HPC) settings, it will also attempt to exploit parallelism, so understanding both is essential for a holistic view of the space in which the proposed project will exist. Definitions included below are a mixture of universal standards used in literature and what will be considered distributed/parallel computing for the purposes of this project.

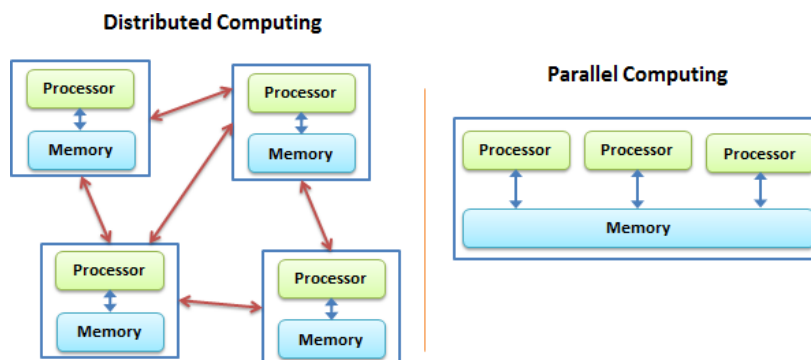


Figure 2.1: Visualization of the difference from [2]

Parallel Computing There are two main modes of parallelism in parallel computing: instruction-level parallelism and thread-level parallelism.

Instruction-level parallelism refers to design techniques at the processor/compiler level that speed the execution of sequential programs by allowing individual machine instructions, e.g. additions, floating point multiplications, memory stores/loads, to execute in parallel [25]. This is typically done using different components of a processor to perform different parts of a given instruction at the same time. Modern processors typically have, at the very least, several floating point units and several integer units, which can handle different parts of the same instruction.

The main distinction between instruction-level parallelism and thread-level parallelism is that instruction-level parallelism occurs at the processor level whereas thread-level parallelism exploits concurrency among multiple processors within the same computer [26]. The thread in thread-level parallelism refers to a thread of execution in which some part of a program runs its code. Threads are different from processes in that threads share the same memory space and are all added to the same existing process. These attributes give threads a distinct advantage over processes when one is working with multiple processors, as an arbitrary number of threads can work on the same shared data structure, either through synchronization or through splitting the structure up into discrete parts [26].

Distributed Computing The distinction between parallel computing and distributed computing is much like the distinction between instruction-level parallelism and thread-level parallelism. Whereas instruction-level parallelism occurs within one processor while thread-level parallelism occurs in a system with multiple processors, parallel computing occurs within one computer while distributed computing occurs across multiple computers. Naturally, new and unique problems arise when a project migrates from a single system of computers to a cluster consisting of multiple computers that are just as challenging as the problems that arise when making sequential code parallel. Common problems include, but are not limited to heterogeneity in networks, hardware, programming languages, or implementation of standard constructs, openness of components within a distributed system, scalability, fault tolerance, concurrency of different resources across different machines, and unique quality of service (QoS) issues relating to availability, reliability, and performance that do not affect applications running on a single computer [27]. Distributed computing can refer to anything from blockchain networks, which distribute verification of information and transactions across many different systems, to web services architectures, in which a web application is broken into modular, discrete components which then run on different computers and communicate across the network, to cloud computing, in which innumerable virtual private servers are spun off and destroyed in tandem across many machines in a massive data center. This project will mainly focus on HPC settings in which memory-intensive scientific applications are run, but hopefully the deliverable will be able to be extended to cloud computing environments, and perhaps even to desktop computer environments if the memory management methods are applicable at this smaller scale. For the purposes of this project, computers with a discrete GPU or other processing component will not be considered distributed computing since many of the aforementioned challenges are less relevant when communicating between components within the same machine - offloading operations to a GPU is analogous to offloading to another CPU core or offloading cache contents to RAM.

2.2 First-Class Distributed Computing in C++

While the most powerful computers in research in industry continue to expand their processor and GPU counts, distributed computing is not yet included as a first class component of the C++ STL [13]. This forces many developers of high-performance scientific applications to reinvent the wheel for each individual project. Common parallel computing constructs, like threads, mutexes, and other locks, went through a similar process in C++. Exploring the history of other attempts to standardize distributed data structures, as well as analogous constructs, is essential to understand the full picture of distributed computing in C++. First, we will detail the existing constructs for parallel and distributed computing and the history of their rise from community-driven tools to first class members of the STL. Next, we will explore recent attempts to add distributed computing paradigms into the C++ STL.

Existing Constructs Despite the lack of distributed constructs and C++, there are many objects used in heterogeneous/parallel computing that serve as important references for any distributed data structures/algorithms. Most important among the aforementioned constructs are `std::async`, `std::future`, `std::atomic`, `std::mutex`, `std::unique_lock`, and `std::thread`, which are detailed in proposals N1682, N1815, N1875, N1883, N1907, N2043, N2090, N2094, N2096, N2139, N2178, N2184, N2885, and N2889, among others [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39]. A great summary and amalgam of all these proposals can be found in N2320 [40]. Figure 2.2 provides a summary of the relationships between these constructs.

To briefly summarize this history, before the ISO C++ STL had any capacity for threading or any concurrency at all, Boost, a popular library that extends the STL, had its own version of threads, locks, and other essentials for concurrency. After the entire Boost community and development team had troubleshooted, iterated, and improved these features in boost, they had an outstanding product with fairly widespread industry adoption. Since the C++ working groups (WGs) have less flexibility and agility in the implementation of a new feature, they did not get around to discussing threading in C++ until after Boost was a full-formed library. As a result, the multi-threading library in the STL is opaquely influenced by Boost. C++ threads, just like boost threads, can be waited on, cooperatively cancelled, quereied, joined with other threads, detached, and otherwise managed. `std::mutex` in C++ is the mechanism by which threads are locked and synchronized. This ISO adoption of Boost standards is encouraging for any developer who wants to spin up a useful open-source library for use in the community, as it demonstrates that libraries with enough widespread community support can eventually become first-class members of the C++ STL.

The idea of a standardized object for resolving an asynchronous subroutine call arose as a result of the fact that though there were many different multi-threading APIs proposed for the C++ standard, each of these libraries made simply calling another subroutine in parallel a difficult task with high code complexity. The intended domain for `std::async` was extracted concurrency in existing programs. There existed, and still exist, a number of applications that are purely sequential, having been written before multi-threading was widely possible, and inserting a function call in a couple of places is usually a more realistic goal than rewriting entire applications with concurrency in mind. N2889 gives the example

of quicksort: `std::async` would be appropriate for recursive calls to quicksort, but not to the iteration in a partition, as it was not intended to compete with existing loop-parallelism solutions. `std::future` is the type returned by a call to `std::async`, and was proposed for this purpose instead of `std::unique_future` to avoid unnecessary overhead with the `unique_future` type. `future` can be thought of as a more primitive thread, in that it doesn't provide any method for synchronization.

Threads are relevant for the purposes of this project since thread-level parallelism will be necessary to maintain any concurrent data structure at a node level. Additionally, passing, cancelling, or locking threads from node to node may be essential depending on the implementation of our concurrent data structures, which seems to indicate that either using some implementation of thread pools or creating our own may be necessary. `std::future` is relevant for work that does not require synchronization, and a distributed implementation of `future` could be interesting, as it could potentially offer easy speed improvements to poorly written HPC applications.

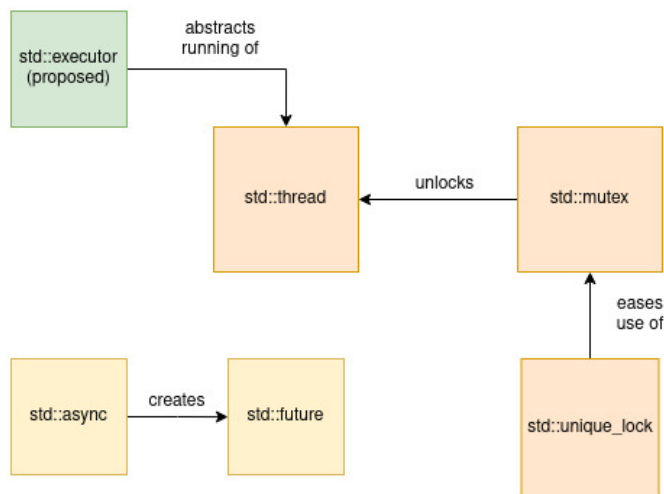


Figure 2.2: Relationships between existing and proposed C++ constructs

Recent attempts Among the most compelling recent attempts to include distributed constructs in the STL is the proposal P0443 [41]. Driven by the increasing diversity and heterogeneity of hardware within almost every system from the newest smart phone to HPC clusters, this proposal suggests the creation of a work execution interface, `std::executor`, and representations of work/the relationships between work, `std::sender` and `std::receiver`. The executor interface could be used to represent anything from a thread pool to SIMD units to GPU runtimes to the current thread. Programmers could author executors by defining their own execution functions for each of these very different environments, and the executor

interface is likely robust enough to provide support for any other execution environments that might arise in the future. Senders and receivers can represent almost any relationships between work in a flow diagram, allowing for the development of more generic code that acts on an asynchronous dependency graph and can be moved seamlessly in-and-out of systems with significant hardware differences.

An interesting addition to P0443 is the application of affinity to executors as described in [13]. In this context, affinity refers to memory access performance between running code and the data accessed by said code. In this context, a resource has higher affinity with a section of memory if access of that section comes with lower latency and/or higher bandwidth [13]. The authors suggest tailoring the executors detailed in P0443 to allow for application developers to preemptively place data/threads in the right place according to affinity, making it so that applications do not have to rely on the operating system to allocate each particular part of memory to the highest affinity segment, perhaps speeding memory access and/or achieving more bandwidth.

While both of these ideas would likely mesh excellently with this project, unfortunately neither have made it into any recent C++ standards. The current C++ machine model is still strictly CPU focused [13], and thus does not account for GPUs or other heterogeneous components, much less other computers. However, the approach of allocating memory based on affinity within an application instead of relying on the operating system is incredibly relevant for this project, as we will likely have to design our solution to optimize affinity on both a node level and a cluster level, where affinity with each big memory node must be accounted for.

2.3 Memory in Distributed Applications

Since the beginning of the information era, there has been rapid development of better CPUs with increased cores and faster clock times in conjunction with an increase in demand of data accesses in many applications [42]. Since the affordability and speed of RAM has not followed that of CPUs, this means that the memory resources in a distributed system are now much more expensive relative to CPU cycles. As a result of this, any interventions that improve the efficiency of accessing and sharing memory, whether at an operating system level or user level, could greatly improve the profitability and efficiency of existing distributed applications. Literature presents several existing improvements to memory usage in distributed applications like [12] [42].

Some of the main challenges in architecture of a shared memory system include coherence enforcement, coherence protocol, processor system interfacing, and interconnection network utilization [43]. In this context, coherence refers to determining which instance of a given piece of memory can be considered accurate. For example, a distributed system may cache 4 redundant copies of the same block of memory on 4 separate nodes to speed reading this block. When one node updates this block of data, all 4 must be notified, and the value must be changed in all of their local caches. Processor system interfacing refers to interactions a distributed application might have with distinct processors on distinct machines. For

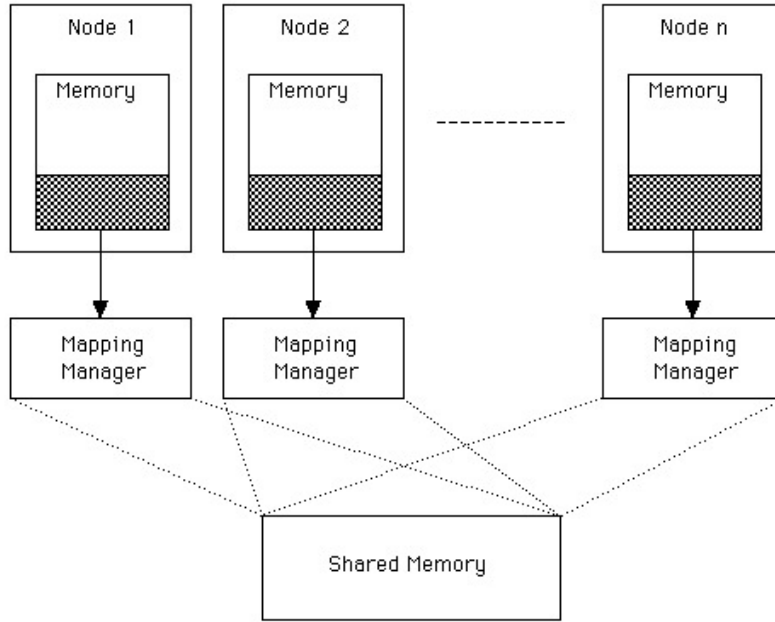


Figure 2.3: Distributed Shared Memory [3]

example, one processor may be little-endian whereas another is big endian. For the purposes of this project, this subtle, yet important, issue will initially be ignored in favor of shipping a viable product for Miami University's cluster, then addressed after a sufficiently featured prototype is working. Extra attention will be paid to using/implementing the most efficient coherence protocol while still achieving acceptable coherence enforcement.

In light of all the potential pitfalls surrounding distributed memory and the abundance of programs that rely more on intensive data access than repeated operations, designing a framework that is intended specifically to work with these kind of specialized applications seems to be a desirable goal.

2.4 Application Binary Interfaces

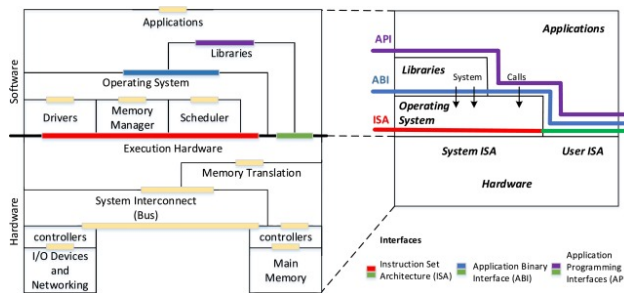


Figure 2.4: Hardware/Software diagram of a typical system. ABI is in blue. [4]

Project	Paradigm	Architecture	Nested	Adaptive	Data Dist.	Scheduling	Continued development
STAPL	S/MPMD	Shared/Dist	Yes	Yes	Auto/User	Customizable	Yes
PSTL	SPMD	Shared/Dist	No	No	Auto	Tulip RTS	No
Charm++	MPMD	Shared/Dist	No	No	User	prioritized execution	Yes
CILK	S/MPMD	Shared/Dist	Yes	No	User	work stealing	No
NESL	S/MPMD	Shared/Dist	Yes	No	User	work and depth model	No
POOMA	SPMD	Shared/Dist	Yes	No	User	pthread scheduling	No
SPLIT-C	SPMD	Shared/Dist	Yes	No	User	user	No
X10	S/MPMD	Shared/Dist	No	No	Auto	-	Yes
Chapel	S/MPMD	Shared/Dist	Yes	No	Auto	-	Yes
Titanium	S/MPMD	Shared/Dist	No	No	Auto	-	No
Intel TBB	SPMD	Shared	Yes	Yes	Auto	work stealing	Yes

Table 2.1: Comparison between different distributed solutions in or resembling C++ [1].

Since the scope of this project is fairly low level, some exploration of how the operating system handles the transfer of data from program to program is necessary, as similar methods will be used when transferring data from machine to machine. Just as an Application Programming Interface (API) defines how users of an application should use exposed methods in a human-readable format, the application Binary Interface defines how programs should use exposed machine methods. AMD’s System V ABI for x86 and x64 systems [44] is one example of how an ABI might look in the real world.

While dealing with ABIs is typically the job of the compiler or the operating system, there are obvious benefits for framework developers who know the ins-and-outs of industry ABIs. For example, if the runtime system for the framework that is developed for this project ends up using caching, and C++ objects have to be transferred around from machine to machine, they will likely have to be transferred in either binary or some condensed form of binary, and we must know how to translate this back into an object that is received into an understandable format for the receiving machine. Knowing at least some basic calls to the ABI could be an essential part of caching objects at a node level, and will likely play a role in our coherence protocol.

Additionally, dealing directly with the application binary interface could prove to be the most performant solution for our program. If we intended to cache data at the node level, we could simply store it in binary, or some compressed binary, format, moving it around from node to node in the cluster and making calls to the ABI to get it into the instance of our application that is running on a particular node.

2.5 Related Work

There exist a number of comparable libraries that have attempted to standardize commonly used distributed/parallel structures, or otherwise create a standard library for distributed computing in C++. Out of all of the libraries initially created to address distributed computing in C++, however, few are still in continued development in 2021. The comparison table lists libraries for distributed and parallel computing in C++. Some of these libraries have

created their own language (Chapel/Cilk) based heavily on C/C++ specifically to support their run-time system (RTS). Others, like Charm++, have created their own interoperable message passing interface for communication between processors and nodes. One additional significant difference not readily visible on the table is that none of these libraries attempt to solve any of the difficulties inherent in memory-bound distributed applications. Additionally, there are numerous solutions dedicated to speeding distributed computing with large in-memory components, including Spark, Memcached, and Globally Addressable Memory (GAM). Brief overviews of the architecture and contributions of each of these solutions are provided below.

2.5.1 STAPL

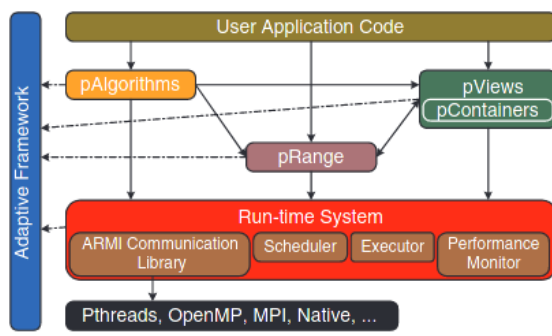


Figure 2.5: STAPL Architecture [5]

Description The Standard Template Adaptive Parallel Library (STAPL) was developed by researchers at Texas A&M University in the late 1990s, far before the C++11 standard provided a set of standardized tools for concurrency. The library was originally created as a super-set of C++’s STL, with the intent to possibly replace the STL on small to medium multiprocessing systems [14]. STAPL is capable of running both single program multiple data (SPMD) and multiple program multiple data applications, and its scheduling algorithm is customizable. STAPL, like the C++ STL, is a generic library, offering data structures and algorithms that can be exploited by a large number of heterogeneous applications. [14]. STAPL implements each distributed data structure as a thread-safe, concurrent object called a pContainer [5].

STAPL pContainers consist of a finite collection of typed elements, storage space, and an interface of methods/procedures that can be applied to the pContainer. [5] Each pContainer is globally addressable, meaning it provides shared memory address space, and can be composed with other containers to create new structures [5]. Distributed data structures implemented by STAPL include an array, a vector, a list, a matrix, a graph, a map, and a set [45] [46]. The library also includes common algorithms for these data structures like those one would find in the C++ STL.

STAPL facilitates communication between data structures and algorithms by having algorithms communicate with pViews through pRanges in the same way that algorithms in the C++ STL communicate with iterators [5]. STAPL represents most algorithms using compositions of algorithmic skeletons, which include many common interaction patterns in parallel programs; for example, map, reduce, zip, and gather [47]. Providing standard, efficient implementations of these skeletons allows users of the framework to focus on the business logic of their program instead of generic patterns. The code sample below includes an example usage of a few of these algorithmic skeletons.

Like many of the other C++ libraries designed with distributed/parallel computing in mind, STAPL provides its own custom runtime system detailed in [48]. One of the main ideas in STAPL’s runtime system is that of a paragraph, which is essentially a directed task graph in which each work items are represented by vertices and dependencies are represented by edges. The runtime system provides executors and schedulers for the tasks detailed in pRanges [1].

Contributions

- **Adaptive Remote Method Invocation (ARMI).** STAPL provides primitives for registering parallel objects and using Remote Method Invocation on them from any cluster machine. This allows for the asynchronous transfer of data and work throughout the distributed system. ARMI utilizes the future and promise constructs detailed in 2.2.
- **Generic Distributed Containers (pContainers).** The STAPL parallel container framework provides a good way of abstracting away the implementation details of a given container on a distributed system, giving users a generic interface that works with any parallel container regardless of the type of system or network on which it exists. In addition to a good interface, STAPL provides its own implementations of containers that stack up well against other industry-standard implementations in scalability and performance trials. [5].
- **Shared Memory Abstraction.** For users who are not working on lower-level applications, STAPL provides an abstraction of the global memory. For more advanced users, STAPL exposes a partitioned global address space (PGAS) architecture.

Big Data Graphs. This is a particularly interesting contribution for this project. STAPL’s graph library [46] provides a novel approach to out-of-core processing for big data graphs in memory-constricted systems, allowing algorithms implemented in this library to efficiently process graphs that do not fit entirely in RAM. STAPL’s parallel graphs use a novel approach that combines RAM and hard disks/SSDs, and works exceedingly well on large distributed memory networks. The approach is comparable to paging, loading subgraphs of a larger graph into available RAM until the whole graph is processed.

Code sample This code solves the first project euler problem, which asks for the sum of all numbers below n that are multiples of 3 or 5. [49]. The code was retrieved from the examples section of STAPL’s Gitlab repository [50].

```
typedef unsigned long long ulong_type;

struct three_five_divisor
{
    template<typename T>
    bool operator()(T i)
    {
        return !((i % 3) == 0 || (i % 5) == 0);
    }
};

stapl::exit_code stapl_main(int, char** argv)
{
    ulong_type num = boost::lexical_cast<ulong_type> (argv[1]);

    // Creates array container of unsigned integers that will be used for storage.
    stapl::array<ulong_type> b(num);

    // Creates view over container.
    stapl::array_view<stapl::array<ulong_type>> vw(b);

    // Fills the container with values from 1 to n.
    stapl::iota(vw, 1);

    // For numbers in the container that return true to the three_five_divisor
    // functor, they are set to 0.
    stapl::replace_if(vw, three_five_divisor(), 0);

    // Adds the total of all elements in container.
    ulong_type total = stapl::accumulate(vw, (ulong_type)0);

    // Prints the total sum.
    stapl::do_once ([&] {
        std::cout << "The total is: " << total << std::endl;
    });

    return EXIT_SUCCESS;
}
```

Listing 2.1: STAPL code sample for Project Euler number 1. Headers and doxygen comments removed for brevity

2.5.2 Charm++

Description Charm++ is a parallel programming framework designed to ease the development, execution, migration, and decomposition of parallel applications [18]. First developed in the early 1990s, Charm++ may have been one of the earliest frameworks to attempt to address distributed computing issues with object-oriented solutions. When Charm++ was first brainstormed, both object orientation and concurrency were still relatively novel. Charm++ was especially innovative among early object-oriented concurrent frameworks in that it allowed for abstractions of modes of information sharing and communication, pro-

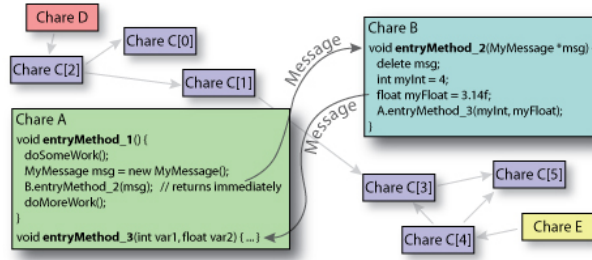


Figure 2.6: Charm++ Architecture [6]

vided support for load balancing and prioritization, and put forth a new "chare" object used for programming common data parallel applications [51].

A chare is essentially a parallel process which can spin up more chares and send messages to other chares. In this sense, the Charm++ framework is only a step above MPI in that it provides additional features on top of the bare-bones parallel process management system. Some of these features include data abstractions for information sharing, such as read-only data, accumulators, monotonic/atomic variables, and distributed tables [51].

Additionally, over a decade before the STL accepted future and async as members, Charm++ included its own implementation of future, which is basically follows the same idea as the STL implementation discussed in 2.2 in that the calling process blocks until the value in the future is computed.

Unlike STAPL and some other framework's in this domain, Charm++'s runtime system is message driven, and every Charm program can broadly be defined, much like MPI, as an initialization and a message-driven loop [52]. In the initialization, the user defines a main chare and branch chare, initializes a memory manager, crafts queue management devices, and deals with load balancing, among other things. In the message driven loop, termed a "pick and process loop", the runtime system essentially acts as a work pool manager, comparable to an executor in a thread pool except with messages instead of threads. Users choose how messages are picked, defining distinct message priorities as necessary for different applications.

Contributions

- **Message driven runtime system.** Whereas many frameworks abstract away the concept of messaging such that the user does not have to deal with it, Charm++ is entirely based around laying messaging bare, and all objects are built around sending and processing messages. While this can induce a learning curve for Charm++, it also makes programs written in Charm++ more readable for advanced users.
- **Latency tolerance through futures.** As mentioned in 2.5.2, Charm utilizes largely the same future construct that is used in the C++ STL. This makes transitioning trivially data parallel applications to Charm much easier, as the futures can simply be swapped out.

Code sample This code prints hello world on a single processor using a single chare in Charm++. It is difficult to show any other simple programs, as Charm++ programs often exist across a header file, source file, interface file, and involve a nontrivial degree of code complexity.

```
// File: main.h
#ifndef __MAIN_H__
#define __MAIN_H__

class Main : public CBase_Main { (1)

public:
    Main(CkArgMsg* msg); (2)
    Main(CkMigrateMessage* msg); (3)
};

#endif // __MAIN_H__

// File: main.c

#include "main.decl.h" (6)
#include "main.h"

// Entry point of Charm++ application
Main::Main(CkArgMsg* msg) {

    // Print a message for the user
    CkPrintf("Hello World!\n"); (4)

    // Exit the application (5)
    CkExit();
}

// Constructor needed for chare object migration (ignore
// for now) NOTE: This constructor does not need to
// appear in the ".ci" file
Main::Main(CkMigrateMessage* msg) { }

#include "main.def.h" (6)

// File: main.ci (interface)
mainmodule main { (7)

    mainchare Main { (8)
        entry Main(CkArgMsg* msg); (9)
    };

};
```

Listing 2.2: Hello World in Charm++ from [6]

2.5.3 X10

Description X10 was developed in 2004 as part of IBM’s Productive Easy-to-use Reliable Computer Systems (PERCS) project, partially because its authors felt that concurrent interactions in languages like Java were too technically complicated to be grasped by the majority of practicing programmers [20]. While the two frameworks mentioned so far attempted to

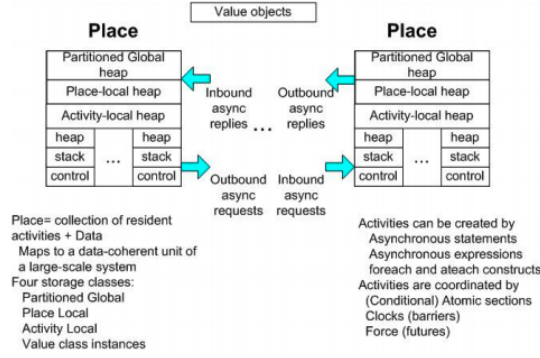


Figure 2.7: X10 Architecture [7]

add access to distributed memory to C++ as part of frameworks, X10 is an attempt to create an entirely new language dedicated to distributed and parallel computing. X10 is not alone in this category: there are a multitude of programming languages or language spin-offs created solely for this purpose, including, but not limited to High Performance Fortran, ZPL, Titanium, Co-Array Fortran, SPLIT-C, Unified Parallel C, and CILK. X10 deserves more of a spotlight than these languages in the context of this project because it is heavily based on C++, the target language for our proposed framework, and because, like the other frameworks outlined here, it had its own approach to sharing distributed memory through a PGAS. X10's language features are largely irrelevant for the purposes of this paper; it suffices to say that X10 is a static, strong, and safely typed compiled object-oriented language that shares many of the features of C++.

An essential concept in X10 is that of a *place*, which is a collection of light-weight threads, termed *activities*, and data. Since the language was designed with high-performance scientific computing in mind, these places were intended to correspond with nodes in a cluster, but could also correspond with one coprocessor in a commercial machine. X10 allocates storage on the activity and place level, with a unified PGAS for remote activities and additional storage allocate for *values*, which are immutable, stateless classes comparable to immutable plain old data (POD) objects in other languages.

X10 replaces locks with "atomic sections", barriers with "clocks", and threads with "asynchronous operations" in an attempt to raise the level of abstraction for standard constructs. Atomic blocks are implemented such that there is a one-to-one relationship between a lock on an atomic block and a place. This means that if an activity from a given place is running within an atomic block, no other activity from the same place will be able to run in the same atomic block. Unlike other language and library solutions for distributed computing, X10 allows for conditional atomic blocks that only activate when a given predicate is satisfied [7].

Contributions

- **Asynchronous calls in place of threads.** X10 largely abstracts the concept of threads away from its users, allowing them to worry instead about entire machines.

Part of this approach is applicable to this project in that asynchronous calls could be used for accessing, modifying, and allocating distributed data structures with the internal thread structure abstracted away from the user.

- **Storage classes.** As mentioned, X10 offers 4 different storage classes: Activity-local, place-local, partitioned-global, and values. This sort of distinction in storage classes is certainly something applicable to this project, as there will have to be some similar scheme for dividing data between nodes and coprocessors, as well as a potential class for data which must be stored on a big memory node.

Code sample This code sample prints a command line argument to all places. Compared to the implementation of Hello World in Charm++, and the Hello World examples in languages with libraries for distributed computing, this offers a relatively low code complexity. There is a trade-off however, in that the language must be made aware of more information about the distributed system on which it is running.

Listing 2.3: Hello World in X10 from [53]

```
class HelloWholeWorld {
  public static def main(args:Rail[String]) {
    finish
      for (p in Place.places())
        at (p)
          async
            Console.OUT.println(p+" says " +args(0));
```

2.5.4 Chapel

Description Like X10, Chapel attempts to solve the problem of providing a standard library for distributed computing through a new language instead of a framework that extends an existing language. Additionally, the design and development of Chapel, like that of X10, was led by an industry leader in high performance computing, Cray Inc. Chapel's original authors believed that the predominant mode of programming for HPC applications at the time, Fortran and/or C/C++ with MPI, was too low-level and demanding for typical programmers, comparing writing MPI programs in these languages to writing assembly code for single sequential processor machines [19].

As mentioned in 2.5.3, there were many languages with the same goal as Chapel, so the authors attempted to differentiate themselves by aiming to outperform these languages while still offering the same abstractions to increase productivity. Chapel's four main goals at design time were to offer support for fine-grain parallelism, provide the infrastructure for locality-aware programming, allow for object-orientation, and allow for generic programming and type inference to simplify the type systems presented to users. Like X10, Chapel removes the notion of a thread from the language, eliminating many concurrent resource management issues from users.

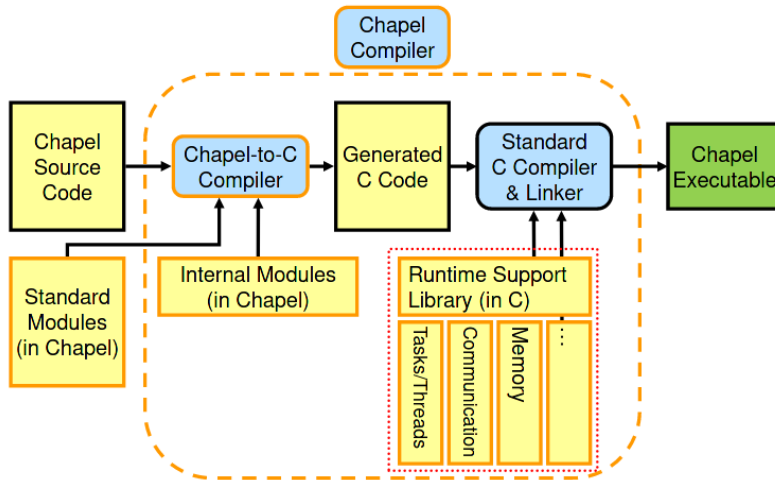


Figure 2.8: Chapel Compilation and Runtime Architecture from [8]

One of the most important concepts in Chapel is that of a *domain*. A Chapel domain is essentially a set of indices that supports parallel iterations [54]. This construct is used to support all of the data structures in Chapel, from sets to arrays to hash tables. Since the concept of domain is far more adaptive than the traditional array in other high-level programming languages, this results in a higher degree of flexibility when working with domains. For example, users can define domains with indexes that are floating points, strings, or references instead of just integers [54].

Chapel’s runtime system has a communication layer that supports inter-locale communicate, PUT/GET operations that work similarly to their HTTP equivalents, and remote fork operations which can be described as the distributed equivalent of the STL implementation of fork on a single system [8]. The runtime system’s tasking layer is another abstraction of the concept of threads similarly to what exists in other libraries, offering synchronization and dependency support - the runtime system offers a distinct, “threading” layer to separate these tasks from the underlying thread programming. The runtime system

Contributions

- **Lightweight processors.** In 1 and 2.3, the prevalence of workloads that are dependent more on memory than processor performance is thoroughly discussed. The authors of Chapel noted this phenomenon as early as their first publication about the language in 2004, calling attention to the fact that large register sets/data caches are focused on a single thread, which can result in unnecessarily large execution state and expensive context switching [19]. In an attempt to remedy this, Cascade provides a distinct class of virtual processor, called a “lightweight” processor, that is optimized for programs which are either rich in short threads/synchronization or data intensive, and is implemented in the memory subsystem. While this project will likely never create a

new virtual processor, this aspect of the Cascade architecture is intriguing, and using parts of this open implementation could be productive.

- **Domain.** Chapel's concept of a domain, while implemented at the language level in their work, could be interesting as a generalization of an array within the context of a distributed C++ framework. Perhaps implementing an array with a more general indexing set as part of the library for this thesis project could lead to higher productivity and lower code reuse.

Code sample This code sample from [55] demonstrates a distributed memory task parallel Hello World program in Chapel.

```
config const printLocaleName = true;

config const tasksPerLocale = 1;

coforall loc in Locales {

  on loc {

    coforall tid in 0\.\.#tasksPerLocale {

      var message = "Hello,␣world!␣(from␣";

      if (tasksPerLocale > 1) then
        message += "task␣" + tid:string + "␣of␣" + tasksPerLocale:string + "␣on␣";

      message += "locale␣" + here.id:string + "␣of␣" + numLocales:string;

      if printLocaleName then message += "␣named␣" + loc.name;

      message += ")";

      writeln(message);
    }
  }
}
```

Listing 2.4: Hello World in Chapel

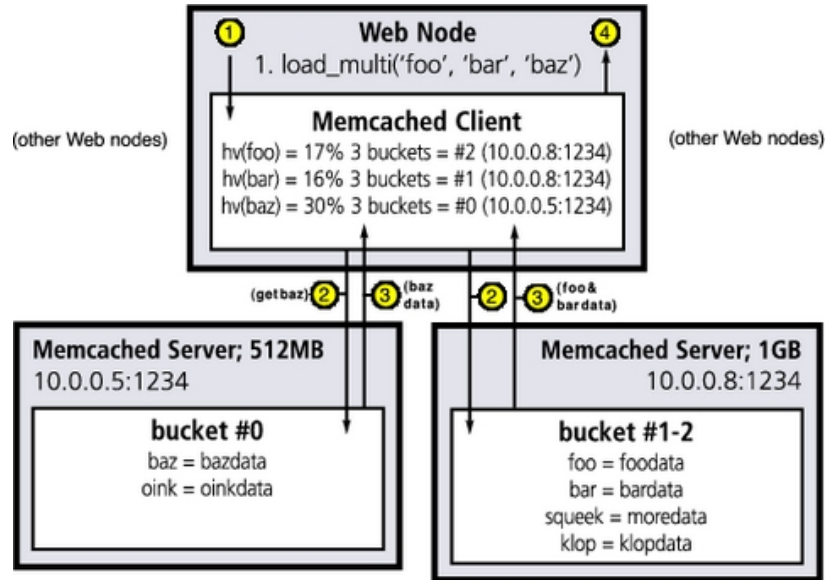


Figure 2.9: Memcached Architecture from [9]

2.5.5 memcached

Description Unlike all of the previous frameworks/languages previously explored, memcached is not a dialect/library of any other language, but rather an application, namely, a daemon, in and of itself. memcached was also originally created by Brad Fitzpatrick, a developer for LiveJournal who was looking to speed the retrieval of objects from memory on a webserver with in-memory caching [56]. The application was first written in Perl, then was rewritten in C when the inefficiencies of Perl became too much.

While memcached was originally only intended to serve pages and data from memory on LiveJournal, its use has expanded to the point where it is now a household name in industry. memcached is used on Twitter, Wikipedia, and many other high traffic sites to alleviate database load. Fitzpatrick recognized early on that CPU cycles were starting to get faster and faster, leading him to valuable to burn them over waiting for comparatively slower disks [9].

Fitzpatrick was able to achieve his goal of using memory and CPU cycles over disk space whenever possible by creating a global hash table in which objects are stored as key-value pairs. memcached instances are run on every server with any memory over a cluster. memcached utilizes a two-layer hash: the first layer decides to which memcached instance a request should be sent by hashing the key onto a list of virtual buckets (each a memcached instance), and then the memcached instance uses a typical hash table [9]. memcached can be run on servers with many different memory sizes, and is relatively machine agnostic, meaning it does not depend upon the endian-ness or instruction set of a machine.

All memcached algorithms are $O(1)$, and it uses a slab allocator for memory allocation, generating slab classes of varying size. Memcached is also lockless, because objects are internally multiversioned and reference counted, meaning that no client can block another

client's actions.

Contributions

- **Redundant and lockless distributed memory.** While many approaches to distributed memory utilize at least some sort of locking mechanism, memcached does not. This allows for a far more usable product, and flattens the learning curve for users, as the only background knowledge needed is how to effectively utilize a dictionary. memcached also provides exceptional redundancy, as any node in a cluster can go down without affecting the performance of the overall service/website.
- **Efficient load-balanced implementation of two-layer distributed hash table.** memcached may be a bit limited compared to the C/C++ libraries detailed earlier, but it does offer an excellent implementation of a distributed hash table. This could serve as a reference implementation for the maps/hash tables in this project.

Chapter 3

Overview and Terminology

As of right now, PC2L will be a **header-only** library. In order to initialize PC2L for a project, one must use the singleton `System` class, which contains system-wide settings, information, and shared objects. Settings on this class will determine the number of nodes that should be used in a run of PC2L. After this class is successfully obtained, the user can start PC2L, use data structures and algorithms, and then close PC2L when its features are no longer necessary, terminating all distributed processes. In this way, PC2L can be easily integrated into any portion of an existing application, allowing users to trivially transition from serial execution on one machine to distributed computing, then back to serial computing again if necessary. In any given instance of PC2L, there can be an arbitrary number of distributed `Worker` objects which handle the message passing work that would typically be done by users in a traditional distributed computing workflow. PC2L also includes a mode in which only one node in a cluster can write data, while the rest of the nodes are used as a distributed cache. This mode of operation allows for maximal utilization of cluster-wide memory and eliminates the potential for write-collisions, making it useful for applications in which a large in-memory data structure is constructed then queried many times.

3.1 Message Passing

The main goal of this thesis is to deliver a portable library for parallel/distributed computing that is optimized for working with data intensive applications. In order to achieve this, we need some form of communication across nodes in a supercomputing cluster and/or processes on a local machine. Instead of reinventing the wheel by developing our own message passing protocol, we will stick with the industry standard Message Passing Interface (MPI) [57]. MPI was standardized by 60 people from 40 top computing organizations across the United States including researchers, computer manufacturers, laboratories, and major companies. Nine versions of MPI have come out since the protocol’s debut in 1994, with varying degrees of acceptance and adoption from the supercomputing community, but its core functionality is used almost universally in all high performance computing projects. Despite MPI’s status as the *de facto* standard for message passing, other alternatives to MPI that have gained more popularity in industry. Among these are Spark [21], Charm++ [18], and ARMCI [58]. However, Charm++ is actually an abstraction over MPI, utilizing it as a hidden backend, ARMCI does not deliver nearly all of the same features as the MPI standard, and, as demonstrated by one recent study of a big memory application in metagenomics [59], MPI applications are typically much faster and much less memory hungry than their Spark equivalents.

In PC2L, the main purposes for message passing will be memory synchronization among nodes and instruction delivery to distributed workers. For instance, a `pc2l::vector` may be stored across several nodes, with distinct or overlapping sub-vectors in each node. If a program is operating on only one section of the vector corresponding to only one node, these changes can be stored in a node-level cache initially, then any caches storing the same data, along with workers operating on this data, can be informed of changes via an update message.

3.1.1 Message Class

Instead of directly interfacing with an MPI implementation through the typical MPI directives, PC2L utilizes a `Message` class for internal consumption that abstracts most of these features away. This level of abstraction allows the underlying MPI commands to be changed without modifying the code in every single file across PC2L. Additionally, it opens the door for version of PC2L that are compatible with different versions of MPI, perhaps utilizing some more recently features in different versions. All of the MPI commands utilized in PC2L are redefined as macros within an internal MPI-helper header.

3.2 Workers

Classes that inherit the `Worker` interface are used to abstract away different kinds of message passing in PC2L. At a minimum, any class that implements the `Worker` interface runs on a process with non-zero MPI rank, sends messages to other `Worker` classes, and contains a buffer used to keep track of received messages. Workers will initially only be concerned with storing and retrieving information from a PC2L instance's distributed Cache, but different `Worker` variations will likely be added as the project progresses and different needs arise.

3.2.1 CacheWorker

A `CacheWorker` in PC2L is responsible for sending and receiving cache-blocks to and from different processes. In order to best utilize the RAM in each separate node, each `CacheWorker` process will be run on a different compute node. When a `CacheWorker` is sent a message to store or retrieve a block of data, it will compute a composite key that combines that data structure type within which the block is stored with a unique block tag generated at run-time, allowing for $\mathcal{O}(1)$ address retrieval for members within a given distributed container.

3.2.2 CacheManager

While there is one `CacheWorker` for every node included in a run of PC2L, there is only one `CacheManager` overall system-wide. The `CacheManager` for a given run of PC2L will run on the process with MPI rank zero, and will coordinate each `CacheWorker` across the system.

Data structures in the program will communicate with the **CacheManger**, which will then schedule tasks to be performed on one of the many **CacheWorkers** using message passing.

Chapter 4

Research Overview

4.1 Proposed Methodology

The main purpose of PC2L is to provide users with distributed implementations of the most essential data structures in the C++ STL. Instead of attempting to implement every single data structure in the STL, we have chosen 3 of the data structures which we believe will be most crucial for general applications for our initial prototype of PC2L. We determine the following data structures to be crucial because many other data structures involve one of them as a component and they are generic enough for use in almost any program. Together with these data structures, we will deliver distributed equivalents of some common STL algorithms that ease their use.

4.2 Vector

From a user perspective, the PC2L vector will mimic the functionality of the `std::vector` detailed in [60] [61]. To briefly summarize these features, the vector will act as a generically typed, variable size array. Users can initialize an empty vector and add an arbitrary number of elements to it. The vector starts with a size of 0, signifying its lack of elements, and a capacity of 1. When the number of elements in the vector reaches the current capacity of the vector, the capacity is expanded by some factor. In many STL implementations, including GNU's G++, the vector is expanded by a factor of two. Other C++ implementations, like Microsoft's Visual C++, choose a rate of 1.5. Most, if not all, implementations of the STL vector necessarily choose to expand capacity exponentially in order to ensure that an element can be added to the end of a vector in amortized constant time. In order to access and modify elements in the vector, users can either obtain an iterator object, use bracket notation, or use the `at` function, which throws an exception if the user attempts to access an invalid element. Elements can be removed or inserted into any position in the vector. STL vectors typically utilize an allocator for storage needs, and can be constructed utilizing different allocators.

In a PC2L vector, the same familiar design pattern described above will be utilized, except utilizing a memory allocator that works across multiple machines, allowing a programmer to construct data structures that far exceed the memory capacity of most individual node computers. When allocating space to the vector, we will prefer to first use one machine, then expand to other machines when the capacity of an existing machine is low. Designing

the vector in this fashion ensures that contiguous runs of elements below a certain size are more likely to be stored in the same machine. As an added feature of the library, we could potentially allow users to specify the proportion of elements in a vector that should be stored in each node.

4.3 Unordered Multi-Map

The idea of a map or dictionary, meaning an associative container which provides $\mathcal{O}(1)$ access, insertion, and deletion, is ubiquitous across most modern programming languages. In C++, the most common map implementation across many programs is likely the `std::unordered_map`, a generic map which utilizes hashing to map a set of unique keys to their respective values. Instead of re-creating this map, we have decided to first implement a version `std::unordered_multimap`, which allows multiple copies of each key value instead of requiring uniqueness, with the understanding that a basic map can later be implemented utilizing a subset of the code from the multi-map. In the STL definition of a multi-map, users can obtain the first element matching a given key using the `find` method, as with any other map. However, utilizing the `equal_range` member method provides users with an iterator that can be used to list all of the values associated with a given key. Users can erase and/or insert key-value pairs, swap the values associated with one key to another key, and count the values associated with a given key. Like the `std::vector`, C++'s `unordered_multimap` can be used with any allocator. Additionally, users can select the predicate for checking key equality as well as the hash functions which dictates where values corresponding to a given key will be stored.

PC2L's implementation of an unordered multi-map will likely utilize the vector structure for storing all values associated with a given key, meaning that the PC2L vector must be complete before development of the unordered multi-map begins. The simplest way to develop an unordred multi-map would likely be a vector of PC2L vectors, in which the hash function returns the location in the top-level vector of the value vector associated with a given key. However, we could potentially obtain better performance at the cost of more disorder by simply randomly storing values in the next available block of memory and maintaining a vector of addresses. This is because we would not have to design for efficient access of contiguous runs within an unordered multi-map, since order obviously does not matter in this structure.

4.3.1 Graph/Tree

While the C++ standard library does not contain any generic graph/tree interface, these data structures are incredibly important in most contemporary programs. After PC2L's unordered multi-map is created, using that structure to support an adjacency list for a graph or tree would be relatively simple. For other applications, it could be useful to provide an implementation of a binary search tree (BST) that could be used to implement ordered sets and/or (multi) maps. In most implementations of the C++ STL, the `std::map`, and `std::multimap`, among others, are supported by a binary search tree.

Overall, we will consider the implementation of top-level graph and tree constructs for implementation only after the vector and unordered multi-map are implemented. As mentioned, PC2L’s vector will support its unordered multi-map, which will in turn support its graph/tree classes if there is enough time to develop them. Additionally, users could even create their own graph/tree equivalents once PC2L delivers a memory allocator, vector, and multi-map.

4.4 Associated Algorithms

Along with generic, robust implementations of common data structures, the C++ STL also provides common algorithms for interacting with said data structures. After developing distributed equivalents of STL data structures, we will begin development of distributed equivalents of algorithms for dealing with those algorithms. In the STL, many of these functions are contained within the `algorithm` header.

Method	Description	Vector	Unordered Multi-Map	Graph/Tree
<code>find</code>	locate an item in a PC2L	Yes	Yes	Yes
<code>reverse</code>	reverse the order of elements	Yes	No	No
<code>swap</code>	exchange elements at given locations	Yes	Yes	Yes
<code>max/min</code>	maximum/minimum element	Yes	Yes	Yes
<code>copy</code>	copy elements to new location	Yes	No	No
<code>reduce</code>	use function to aggregate range	Yes	No	No
<code>map</code>	apply function to each element	Yes	Yes	Yes
<code>bfs/dfs</code>	iterator for breadth/depth-first search	No	No	Yes
<code>dijkstra</code>	iterator for shortest path using dijkstra	No	No	Yes
<code>mst</code>	tree that connects all nodes with minimum weight	No	No	Yes

Table 4.1: Structures in which each algorithm is implemented

Table 4.1 describes some of the algorithms that we plan to implement within PC2L. These are subject to change, which might include addition, subtraction, or modification. Drawing inspiration from [14], as well as industry-standard big-data processing programs like Hadoop, we have chosen to implement two essential algorithmic skeletons, `map`, which is not implemented in the STL, and `reduce`, which is. Additionally, we have chosen to distributed equivalents of several simple graph algorithms for the PC2L graph such that users do not have to worry about creating these on their own.

4.4.1 Distributed Memory Allocator

For each data structure implemented in STAPL, we will have to allocate memory proportional to the number of generic elements in said data structure. In the C++ STL, this is done using a `std::allocator`, which can allocate and release blocks of storage, give addresses for said blocks of storage, and construct/destruct objects. `std::allocator` expects **contiguous memory allocation**, meaning that blocks of memory are allocated in a strict linear order

such that pointer arithmetic works as expected. Each C++ STL container must utilize some implementation of the allocator interface, and a default one is provided if the user does not suggest one.

In keeping with the theme of providing distributed equivalents of standard library data structures, PC2L will provide a distributed implementation of `std::allocator`. This will be the default allocator for PC2L data structures, and it will also be able to be used on STL data structures, albeit with perhaps inferior performance. A simple, prototypical allocator could create a new addressing system by numbering each node in a run of PC2L and concatenating node number with an address provided by a conventional allocator within that node. Again, one important consideration for any implementation of `std::allocator` is ensuring that pointer arithmetic works as expected. With this in mind, we may have to override some operations for PC2L pointers so that they work as expected.

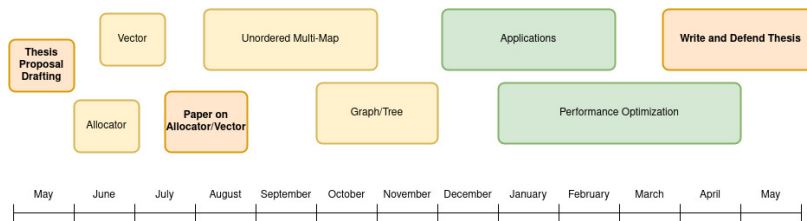


Figure 4.1: Thesis timeline

4.5 Dissemination of Results

We plan to split the results into two separate sections: an initial paper, which will cover the details of `pc2l::vector` and `pc2l::allocator`, and the full thesis, which will cover the complete implementation, optimization, and application of all data structures in PC2L. We will submit abstracts/drafts of the final thesis paper to the ACM Symposium on the Principles of Distributed Computing, IEEE International Parallel and Distributed Processing Symposium, and the ACM International Symposium on High Performance Distributed Computing. We will submit the paper on `pc2l::allocator` and `pc2l::vector` to IEEE Transactions on Parallel and Distributed Systems (TDPS), Springer’s Distributed Computing, and Elsevir’s Journal of Parallel and Distributed Computing. All of these submissions will be standard journal articles. Additionally, the complete thesis will be published to OhioLink, as is standard for graduate theses from this department.

4.6 Validation

While PC2L may sound great so far, we are in desperate need of some objective measurables that can demonstrate its efficiency, scalability, and usability. The goal will be to maximize each of these three key attributes, hopefully enough that they exceed comparable measurements for competing libraries.

4.6.1 Performance Comparison with Sequential Equivalents

First, we will compare PC2L data structures with their sequential equivalents in the C++ STL. We will do this through several unit tests which fill, remove, and find elements within several of PC2L’s data structures. Of course, some data structures, like the `pc2l::graph` will not have an exact sequential counterpart, in which case they will be compared to any data structure with common features, or reference libraries that implement the same structures. We expect sequential data structures to beat PC2L when a smaller number of elements is inserted into a data structure, but we expected PC2L to prevail as the number of elements in a data structure grows.

4.6.2 Adaptivity Assessment

Users will be able to customize caching in PC2L such that the elements that are cached best suit the access pattern of their project. In an attempt to evaluate whether this feature is actually adaptive to different access patterns, we will test different access patterns against different feature settings. For example, we could test a sequential access pattern against sequential caching, then test a regional access pattern against sequential caching, and so on and so forth. Ideally, we expect these tests to demonstrate that PC2L offers better performance when a user specifies the access pattern for their data structure.

4.6.3 Scalability Measurement

In order to ensure that PC2L works at scale, we will put it through several different tests. First of all, we will generate several believable programs that are data-intensive, and perhaps find a real application from another project. Next, we will adapt these programs to utilize PC2L data structures. Finally, we will measure how the performance of each of these programs changes as nodes, processor cores, and memory are added to a run of PC2L. If designed properly, we expect PC2L to deliver better performance with each additional resource it is given. Additionally, this sort of testing can support the development process as we can graph program performance and identify if PC2L ever runs into a performance plateau after adding any number of additional resources.

4.6.4 Usability Measurement

Above all, PC2L is a library designed for user consumption. Any library we make will be essentially useless outside of our lab unless we can convince real users to adopt it. This is where our measurement of usability comes in. After PC2L is fully develop, we will find both experienced and novice distributed computing developers, hand them the documentation, and have them evaluate how usable PC2L is across several different criteria. There are several different major usability metrics that come up in [62] including efficiency, effectiveness, productivity, satisfaction, learnability, safety, trustfulness, accessibility, and usefulness.

While these criteria are typically used for non-technical, consumer-facing products, we can adapt some of them for our purposes

4.6.5 Stopping Criteria

Although all of these evaluation criteria are important, the main metric we will use to determine a stopping point will be performance and scalability. We have made this choice because although changing syntax and/or adaptability features will be trivial once the full implementation is complete, changing core features will not be so easy. With this in mind, we will leave achieving ideal usability and adaptivity to future researchers, and instead focus on achieving similar, if not better, scalability and performance when compared with other frameworks. More specifically, PC2L will be complete when it can compete with and/or beat competing distributed computing frameworks in stress test utilizing memory-intensive, big memory applications.

Chapter 5

Conclusion

In summary, PC2L will be a C++ framework that provides standard, distributed data structures comparable to those found in the C++ STL. Through exploration of numerous alternative libraries that attempt to achieve this goal, we extracted many contributions in the form of useful constructs and design patterns. We listed and justified the initial set of data structures that will be implemented in PC2L. We provided a description of the underlying concepts common to each of these data structures. We provided a timeline for the development of PC2L, stopping criteria for finishing work on PC2L, and evaluation criteria for demonstrating the usefulness of the library.

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