HabaneroUPC++: a Compiler-free PGAS Library

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The Partitioned Global Address Space (PGAS) programming models combine shared and distributed memory features, providing the basis for high performance and high productivity parallel programming environments. UPC++ [39] is a very recent PGAS implementation that takes a library-based approach and avoids the complexities associated with compiler transformations. However, this implementation does not support dynamic task parallelism and only relies on other threading models (e.g., OpenMP or pthreads) for exploiting parallelism within a PGAS place.

In this paper, we introduce a compiler-free PGAS library called HabaneroUPC++, which supports a tighter integration of in-place and inter-place parallelism than standard hybrid programming approaches. The library makes heavy use of C++11 lambda functions in its APIs. C++11 lambdas avoid the need for compiler support while still retaining the syntactic convenience of language-based approaches. The HabaneroUPC++ library implementation is based on a tight integration of the UPC++ library and the Habanero-C++ library, with new extensions to support the integration. The UPC++ library is used to provide PGAS communication and function shipping support using GASNet, and the Habanero-C++ library is used to provide support for in-place work-stealing integrated with function shipping. We demonstrate the programmability and performance of our implementation using two benchmarks, scaled up to 6K cores. The insights developed in this paper promise to further enhance the usability and popularity of PGAS programming models.

Categories and Subject Descriptors
D1.3 [Programming Techniques]: Concurrent Programming – distributed programming; parallel programming; D3.3 [Programming Languages]: Language Constructs and Features – concurrent programming structures; D3.4 [Programming Languages]: Processors – compilers; optimization; run-time environments

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General Terms
Design, performance

Keywords
PGAS, UPC++, Habanero, scheduling, work-stealing

1. INTRODUCTION

The Partitioned Global Address Space (PGAS) programming model [2] strikes a balance between shared and distributed memory models [26]. It provides ease of programming due to its global address memory model and performance due to locality awareness. Languages belonging to this category include Co-Array Fortran [23], Titanium [37], UPC [10], X10 [6] and Chapel [5]. They rely on compiler transformations to convert the user code to the native code. Some of these languages, such as Titanium, X10 and Chapel, use code transformations to provide dynamic tasking capabilities using a work-stealing scheduler [22, 12, 18, 19, 27, 4] for load balancing of the dynamic tasks. Min et al. introduced API based dynamic tasking library for UPC [21]. However, it lacks the expressiveness of the X10’s async-finish style dynamic tasking. Co-Array Fortran does not allow dynamic tasking but permits the user to use OpenMP libraries for achieving loop-level parallelism.

The library approach to PGAS programming makes it easier to interoperate with other programming models such as MPI [7], CUDA [24] or even other PGAS languages. It also avoids the significant development and maintenance costs associated with a language-based approach. In addition, the compiler-free approach facilitates adding new features and combining multiple packages. UPC++ [39] is a very recent PGAS approach, implemented as a C++ library. However, UPC++ does not allow intra-place dynamic tasking. It introduces inter-place asynchronous copy and asynchronous function shipping, with the limitation that these asynchronous activities don’t automatically migrate (e.g., no work-stealing) and finish doesn’t track transitively spawned descendant activities by default as in X10’s async-finish. For intra-place loop parallelism in UPC++, the user relies on other threading models (e.g., OpenMP or pthreads).

Work-stealing schedulers have emerged as the approach of choice for dynamic load balancing. Within the underlying language runtime they use a fixed size worker pool to schedule the work exposed by the programmer, exploiting idle processors and unburdening those that are overloaded. Habanero-Java [4] and Habanero-C [28] implement X10 style async-finish tasks for shared memory. A variant of Habanero-C called HCMPI [7] provides SPMD programming model using intra-node async-finish parallelism and MPI for inter-node parallelism. However, HCMPI relies on

1We use place to represent each independent execution unit in UPC++ and threads to represent work-stealing workers.
compiler transformations and by using MPI it does not get the benefits of the PGAS programming model.

The main contributions of this paper are: a) Habanero-C++ library, a compiler-free approach for using Habanero work-stealing using C++11 lambda functions; b) HabaneroUPC++, a new PGAS library combining the benefits of Habanero-C++ and UPC++, and allowing the programmer to conveniently and concisely expose dynamic task parallelism in a highly scalable PGAS implementation; and c) evaluation of HabaneroUPC++ using two benchmarks, scaled up to 6K cores.

The rest of the paper is structured as follows. Section 2 provides the relevant background. Section 3 summarizes the Habanero-C++ programming model. Section 4 explains the details of our runtime. Section 5 evaluates HabaneroUPC++ performance on the Edison supercomputer at NERSC. Section 6 discusses the related work and, section 7 concludes the paper.

2. BACKGROUND

2.1 Habanero-C

Habanero-C language provides a finish-async task-parallel programming model [4] for exploiting intra-node parallelism. Here we briefly describe some of its features related to this paper, more details can be found in [28]. Habanero-C is based on Habanero-Java, which itself was derived from an earlier version of X10. Figure 1 shows the different dynamic tasking constructs available in Habanero-C.

The async is used to create a child task asynchronously to execute Statement. finish is used to join all async tasks, including the transitively spawned ones. Habanero-C uses compiler transformations to translate these dynamic tasking constructs from user code to runtime calls. The local variables declared outside of the async scope can be accessed inside of the async by using IN/OUT/INOUT clauses. IN declares a variable as read-only, OUT specifies write-only and INOUT specifies both read and write access. The place can be used to specify a node within a hierarchical place tree [35] (intra-node only). The AWAIT clause can be used for data-driven task (DDT) synchronization [33]. async with AWAIT clause gets executed only when all the ddf (data-driven futures or DDFs) have been satisfied (written using a put operation). The phased clause registers an async with phasers [29] specified in the list with the corresponding modes. If empty phaser list is specified then it registers the async on all the phasors of the parent task. The phased async is executed only when the signal modes are satisfied on the listed phasors.

forasync construct is similar to a program loop which exhibits parallelism. The point clause specifies the loop indices in each dimension. Total number of iteration in each dimension is specified using the size clause. The clause seq specifies the tile size. The runtime can be instructed to schedule forasync in two ways, chunked scheduling and recursive scheduling. In chunked mode the loop iterations are chunked into blocks of length specified by seq clause whereas in recursive mode the iterations are recursively partitioned until size matches seq value.

Figure 1: Dynamic tasking constructs in Habanero-C.

2.2 OCR

Studies suggest future high performance computing systems would scale to exascale. These exascale systems would contain attributes that would be 1000 times the value of similar attribute of a petascale system from the year 2010 [1]. These systems will be massively multicore per chip. Their performance will be driven by parallelism, constrained by energy and data movement. Open Community Runtime (OCR) [25] is an open-source, multi-institutional project aimed at creating a common set of runtime APIs for task-parallel programming models suited for the exascale systems. These APIs can be either targeted by a compiler for a high-level programming language, or called directly by a hero programmer writing an application directly in OCR.

OCR also supplies a reference implementation that uses the ideas from the Habanero-C (Section 2.1) work-stealing runtime to implement non-blocking load-balancing of tasks across different processors. As of this writing, there are OCR implementations on x86 shared-memory multiprocessors and on clusters of x86 machines.

The main concepts in OCR are:

1. Tasks. Event-driven tasks (EDTs) are the units of computation in OCR. All EDTs have to declare a set of dependencies to which external events can be connected. An EDT does not begin execution until all its dependencies have been satisfied. EDTs are intended to be functional, non-blocking pieces of code. Internally, they can exploit some other form of parallelism (such as data parallelism) but they should communicate with other EDTs only by using Data Blocks and Events defined below. All EDTs have a globally unique ID (GUID) that identifies them across the system.

2. Data. Data Blocks (DBs) are the mechanism for storing and communicating data between EDTs. DBs are identified by a GUID as well. Since DBs can be relocated and replicated by the runtime for performance, energy or resilience reasons, it is essential that all user data is expressed in terms of DB GUIDs and offsets within DBs instead of pointers as in traditional shared-memory systems.

3. Events. Events are the mechanism for creating data and control dependencies in OCR. When an EDT’s dependence is connected to an event, the runtime is informed that that particular EDT depends on that particular event, and the EDT will not execute until that event is satisfied. An EDT performing a put on an event can satisfy that event. A put on an event can be empty (used for triggering the execution of EDTs waiting on that event, i.e. implementing control dependence) or it can take DB GUID as a parameter (used to pass data to the EDTs waiting on that event, i.e. implementing data dependence). Each event has a GUID as well.

The programmer (or compiler) creates an OCR program by constructing a dynamic graph of EDTs, DBs and events. There are currently several higher-level parallel programming models that map onto OCR, including CnC [14], HCLib [3], HTA [11] and RStream [20]. This paper demonstrates the integration of OCR (through the use of the HCLib Habanero implementation built on top of OCR) with the UPC PGAS programming model.
Memory model and the SPMD execution model from UPC. Each
programming languages and libraries. UPC++ adopts the PGAS
standalone programming system for developing PGAS C++ ap-
2.4 UPC++
Underlying execution runtime.
presentation. HClib relies on OCR to configure and bootstrap the
asynchronous task types is transformed into a generic EDT rep-
second layer. In this layer, the API call for any of the Habanero's
layers: HClib; HClib on OCR; and OCR. The first layer defines
also packed in a list.
local variables from outer scope, which are to be accessed inside
inside a function, which the OCR runtime can execute. All the
user APIs. It is agnostic to the under-
HClib data-structures and user APIs. It is agnostic to the under-
pointers to OCR. Similarly, all the DDFs and phasers are
“void” pointer to OCR. Similarly, all the DDFs and phasers are
also packed in a list.
The HClib library is built on top of OCR. It is composed of three
layers: HClib; HClib on OCR; and OCR. The first layer defines
HClib data-structures and user APIs. It is agnostic to the under-
lying runtime it executes on. The second layer acts as a bridge
between HClib and OCR. This layer knows about the OCR run-
time and translates HClib actions into OCR ones. The third layer
is the OCR runtime, which is the supporting execution platform.
Most of the interaction between HClib and OCR happens in the
second layer. In this layer, the API call for any of the Habanero’s
asynchronous task types is transformed into a generic EDT rep-
resentation. HClib relies on OCR to configure and bootstrap the
underlying execution runtime.

2.4 UPC++

UPC++ is a PGAS C++ extension, which can be used as a
standalone programming system for developing PGAS C++ ap-
lications or as a runtime component to support other high-level
programming languages and libraries. UPC++ adopts the PGAS
memory model and the SPMD execution model from UPC. Each
UPC++ place has its private address space and a partition of the
global address space, in which data is directly accessible by all
UPC++ places even on distributed-memory systems. Here we give a
brief overview of UPC++ features used in HabaneroUPC++ about
global data sharing, one-sided communication, and remote func-
tion invocation (a.k.a. function shipping). Table 1 lists the essential
UPC++ programming constructs.

In the UPC++ PGAS memory model, shared objects can be de-
clared statically at compile time or allocated dynamically at run
time. UPC++ shared data types are implemented as generic tem-
plates parameterized over the object type, which can be either built-
in types or user-defined types (e.g., class. shared_var<T> type
of data are physically located in the same global partition as in
UPC, and shared_array<T> type of data are block-cyclically dis-
tributed across all global partitions. UPC++ shared_array can be
initialized with dynamic size and blocking factor at runtime
(e.g. sa.init(N, BF)). The default blocking factor of UPC++
shared arrays is 1 (cyclic distribution) and it can be changed with
shared_array member function set_blk_sz. The subscript op-
erator[] is overloaded to provide the same accessing rules as non-
shared arrays. In addition, shared_array can be declared (collec-
tively) inside a function scope. Due to its SPMD nature, UPC++
shared variable names can be referenced from different processes,
which provides a convenient way for communication and synchro-
nization. Regardless of their physical location, shared objects are
accessible by any UPC++ place.

Dynamic global memory allocation is done through generic
global pointer type (global_ptr<T>) which points to a shared
object of type T. A global pointer encapsulates both the process
place and the local address of the shared object referenced by the
pointer. Pointer arithmetic with global pointers in UPC++ works
the same way as arithmetic on regular C++ pointers. Global ad-
dress space memory can be allocated and freed at any place by
allocate and deallocate templated functions.

Communication in UPC++ applications may appear in two forms:
1) explicit data transfer using one-sided copy functions;
2) implicit data communication when shared objects appear in an
expression. For example, if a shared object is on the left-hand-
side of an assignment statement then it’s equivalent to a put op-
eration. Likewise, it is a get operation if the shared object is on
the right-hand-side. In UPC++, the type conversion operator to
the local object type (operator T()) is overloaded for accessing
remote shared objects. The user can initiate bulk data movement
operations using the copy function or its non-blocking counterpart
async_copy function, for which the src and dst buffers are as-
sumed to be contiguous. async_copy enables overlapping com-
munication with computation or other communication. The com-
pletion status of async_copy can be queried by async_try or

Table 1: Basic PGAS primitives in UPC++

<table>
<thead>
<tr>
<th>Programming Idiom</th>
<th>UPC++</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of places</td>
<td>ranks()</td>
</tr>
<tr>
<td>My ID</td>
<td>myrank()</td>
</tr>
<tr>
<td>Shared variable</td>
<td>shared_var&lt;Type&gt; v</td>
</tr>
<tr>
<td>Shared array</td>
<td>shared_array&lt;Type&gt; a(count)</td>
</tr>
<tr>
<td>Global pointer</td>
<td>global_ptr&lt;Type&gt; p</td>
</tr>
<tr>
<td>Memory allocation</td>
<td>allocate&lt;Type&gt;(place, count)</td>
</tr>
<tr>
<td>Data transfer</td>
<td>async_copy&lt;Type&gt;(src, dst, count)</td>
</tr>
<tr>
<td>RPC</td>
<td>async(place)(Function, args...)</td>
</tr>
<tr>
<td>Synchronization</td>
<td>async_wait() / async_try() / barrier()</td>
</tr>
</tbody>
</table>
habit and the user provides its lower-

C++ provides support for the accumulators [30] and places [35]. Similarly, Habanero-

capture-list of lambda functions provides a mechanism to pass vari-

variables can either be captured by reference or by value. Passing a

which we want to use inside statements

Syntax "" captures all the local variables by value.

Habanero-C. Figure 3 shows the Habanero-C++’s equivalent of the

3. HabaneroUPC++ Programming Features

In UPC++ the execution units (place) are single threaded un-

3.2 HabaneroUPC++ Programming Features

3.2.1 Asynchronous Remote Copy

As discussed in Section 2.4, UPC++ provides a non-blocking

copy function. To be able to integrate with Habanero-C++, we pro-

3.1 Habanero-C++ Dynamic Tasking Library

Habanero-C++ uses C++11 lambda functions to express

Habanero-C dynamic tasking constructs (Section 2.1). As we take

a compiler-free approach, the program syntax slightly differs from

Habanero-C. Figure 3 shows the Habanero-C++’s equivalent of the

Habanero-C’s dynamic tasking constructs shown in Figure 1. The

syntax “[capture_list()]” marks the beginning of a C++11

lambda function. The capture-list contains the list of variables, which we want to use inside statements $S_1, S_2, S_3$ and $S_4$. These variables can either be captured by reference or by value. Passing a single "&" as the capture-list captures all the local variables by refer-

cence while passing a "=" captures all the local variables by value. Asynchronous tasks do not return values. However, parameter-

result variables can be passed as references in the capture-list. The capture-list of lambda functions provides a mechanism to pass vari-

ables to an async that is semantically equivalent to the usage of the

IN/OUT/INOUT clauses of Habanero-C. Relying on C++11 fea-

tures, Habanero-C++ currently provides support for async’s AWAIT

and PHASED clauses. The implementation can be further extended to

support accumulators [30] and places [35]. Similarly, Habanero-

C++ provides support for the forasync construct (Figure 3). The

dim argument to the forasync call specifies the loop dimension. The

style argument specifies whether to use the chunked or recur-

sive scheduling. For each dimension, the user provides its lower-

Figure 3: Dynamic tasking using C++11 lambda functions.

waitated by async_wait. Finally, user may register an async_copy

operation with an event that can be synchronized later. UPC++

also provides MPI-style collective operations implemented on top

of the GASNet collectives API.

An important new feature in UPC++ but not in UPC is re-

mote function invocation. The user may start an asynchronous

remote function with the async construct and specify dependen-

cies among distributed tasks using the event mechanism similar to

Phalanx [13]. Each async function call may be registered with

an event that will be signaled after the remote function is com-

pleted, and used as a precondition to launch later async operations. 

UPC++ remote function invocation is implemented on top of GAS-

Net active messages.

3. HabaneroUPC++ PROGRAMMING

MODEL

In this section we first describe the Habanero-C++ dynamic task-

ing library. Being a C++ library, Habanero-C++ easily integrates

with UPC++ and offers a highly scalable PGAS implementation,

which we refer to as HabaneroUPC++. We also discuss the fea-

tures of this new programming model.

3.2 HabaneroUPC++ Programming Features

In UPC++ the execution units (place) are single threaded un-

less combined with OpenMP to achieve the loop level parallelism. 

This style of parallelism is restrictive and does not enjoy the ben-

efits of work-stealing schedulers. Other kinds of parallelism

can be effectively load-balanced using work-stealing and include di-

vide and conquer, irregular graph computations and loop paral-

lelism. HabaneroUPC++ integrates the benefit of Habanero-C++’s

work-stealing library in UPC++. Similar to UPC++, the Haba-

roUPC++ program also starts in a SPMD fashion, where each place 

gets a copy of the main function. Taking UPC++ as baseline, we

will now discuss our newly added features.

3.2.1 Asynchronous Remote Copy

As discussed in Section 2.4, UPC++ provides a non-blocking

copy function. To be able to integrate with Habanero-C++, we pro-

vide a variant of this as shown in Figure 4(a). The optional DDF

allows launching an asyncAwait, which gets scheduled only when the 

asyncCopy is complete.

3.2.2 Asynchronous Remote Function Invocation

UPC++ provides its own version of async for remote function

invocations. However, these remote async does not capture the

close of the async spawn. Moreover, threads within a UPC++

place cannot call them concurrently. HabaneroUPC++ provides a 

variant of UPC++’s async. This is called asyncAt and its syntax is 

shown in Figure 4(b). This asyncAt can be nested, they are thread-

safe, and can also calls Habanero-C++’s async inside the lambda 

function.

3.2.3 Joining Asynchronous Tasks

To be able to join all the asynchronous tasks (async, 

asyncAwait, asyncPhased, forasync, asyncAt and

asyncCopy), HabaneroUPC++ provides a special version of

finish called as finish_spmd, shown in Figure 5. finish_spmd 

waits for all the dynamically spawned asynchronous tasks in

its scope, which includes remote asynchronous tasks as well. 

HabaneroUPC++ also allows arbitrary nesting of finish inside

finish_spmd. However, this finish only allows the launch of 

Habanero-C++ asynchronous tasks and no remote asynchronous 

tasks.

3.2.4 Collective Communications

For collective communications, HabaneroUPC++ relies on

UPC++ collectives and does not modify their default implementa-

tion. However, HabaneroUPC++ restricts the usage of collec-

(a) Asynchronous copy with optional DDF

asyncCopy(global_ptr<T> src, global_ptr<T> dst, 
size_t count, DDF* ddf=NULL);

(b) Asynchronous remote lambda invo-
cation

Figure 4: Remote asynchronous calls.
```cpp
finish_spmd ([capture_list](()) {
    async(...); // local
    asyncAwait(...); // local
    asyncPhased(...); // local
    forasync(...); // local
    asyncCopy(...); // remote
    asyncAt(...); // remote
});
```

Figure 5: Joining of asynchronous tasks using special finish.

```cpp
void async_wrapper(void* args) {
    // Cast the lambda object
    std::function <void()> *lambda = (std::function<void()>) args;
    // Execute the lambda
    (*lambda)();
    delete lambda;
}
```

```cpp
void schedule_async(bool inter_place ,
    std::function <void()> lambda) {
    // Heap allocate a lambda object
    // as currently its on stack
    std::function <void()> * lambda_copy = new std::function <void()> (lambda);
    // bookkeeping: OCR increments async count
    // which decrements once this task has executed
    runtime(inter_place , async_wrapper , lambda_copy);
}
```

```cpp
void async(std::function <void()> lambda) {
    // Pass the lambda to work-stealing runtime
    // as an inter-place asynchronous task
    schedule_async(false, lambda);
}
```

Figure 6: Implementation of async

```cpp
void asyncCopy(global_ptr <T> src,
    global_ptr <T> dst,
    size_t count, DDF_t* ddf=NULL) {
    atomic(outgoing_tasks++);
    // Create a lambda to execute UPC++ calls
    auto lambda = []() {
        // Use UPC++ active message to invoke
        // asyncAt_wrapper at toPlace
        upcxx::async(toPlace)(asyncAt_wrapper <T>,
            remote_lambda);
    };
    // Schedule an inter-place async task
    schedule_async(true, lambda);
}
```

Figure 7: Implementation of asyncCopy

```cpp
declare (void* ddf) {
    if(ddf != NULL) DDF_PUT(ddf);
    atomic(incoming_tasks++);
}
```

4. IMPLEMENTATION

The previous section explains the HabaneroUPC++ programming model. In this section we describe the implementation of the HabaneroUPC++ runtime.

4.1 Translating C++11 Lambdas to Runtime Calls

HabaneroUPC++ takes a compiler-free approach. Hence, the API exposed to the user relies on a set of HabaneroUPC++ runtime calls that can handle C++11 user-defined lambdas. In a nutshell, the C++ compiler converts a lambda function into a class with an overloaded "()" operator, which acts as a function. The variables captured (e.g., capture_list in Figure 3) in the lambda definition become member variables of this class. This class also has access to all the global variables in the program scope. The variables can be captured either by value or by reference. In case an object is captured by value, then the copy constructor is called when the lambda closure is created. The code to create lambda closure is automatically generated by the C++ compiler. By default all variables captured by value are immutable, unless the mutable keyword is explicitly used. Passing a lambda as a function parameter is similar to passing a class object. A detailed explanation of the C++ implementation of lambdas is available in [16].

We now describe how the user lambda function gets communicated to the runtime. The runtime treats lambda functions dif-

```cpp
// Executes at destination
template <typename T>
void asyncAt_wrapper(global_ptr<T> remote_lambda) {
    // Allocate memory in myPlace's partition
    // in global address space
    upcxx::global_ptr<T> my_lambda = upcxx::allocate<T>(myPlace);
    // Copy the lambda in memory allocated above
    upcxx::copy(remote_lambda, my_lambda);
    // Execute the lambda
    (*T*)my_lambda();
    // Free memory allocated for lambdas
    dealloc(my_lambda);
    dealloc(remote_lambda);
    atomic(incoming_tasks++); // bookkeeping
}
```

Figure 8: Implementation of asyncAt

```cpp
// Executes at source once asyncCopy is complete
void perform_ddfWrite(void* ddf) {
    if(ddf != NULL) DDF_PUT(ddf);
    atomic(incoming_tasks++); // bookkeeping
}
```

```cpp
// Create a lambda to execute UPC++ calls
auto lambda = []() {
    // Use UPC++ asynchronous copy function
    // to perform remote copy and tie it with
    // a UPC++ event object
    upcxx::event e;
    upcxx::async_copy(src, dst, &e);
    // Attach a callback function which waits
    // on event e. Once async_copy is done, this
    // callback executes at current place and
    // launches function perform_ddfWrite with
    // ddf as parameter
    upcxx::after(myPlace, &e)(perform_ddfWrite,
        (void*) ddf);
};
```

Figure 8: Implementation of asyncCopy
ferently depending on whether they represent asynchronous tasks to be executed locally (async, asyncAwait, asyncPhased and forasync) or remotely (asyncAt and asyncCopy). Figure 6 shows the implementation of the async construct. Because an async is potentially executed after its creation context is done executing, the runtime cannot rely on any variables that may have been stack allocated. For that reason, the runtime creates a heap-allocated copy of the user-defined lambda. Once the lambda is passed to the work-stealing runtime, the worker threads can execute it by calling the async_wrapper function and use the overloaded “()” operator to convert the lambda into a function call. The lambdas for asyncAwait, asyncPhased and forasync are treated in similar fashion, but they can also take a variable number of arguments. For instance, asyncAwait can get multiple DDFs; asyncPhased can have multiple phasers and signal modes; and forasync can be of any dimension. To that effect, the runtime provides several copies of asyncAwait, asyncPhased and forasync, each accepting a different number of their respective arguments.

The implementation of asyncAt is as shown in Figure 7. If the source and destination places are same, the lambda is scheduled as a local async. The other case is treated differently. A std::function class template (Figure 6) is a general purpose polymorphic function wrapper whose instances can store, copy and invoke lambdas. In the case of asyncAt both the lambda closure object and the std::function pointer are required for remote execution. The C++ compiler creates a separate class for each lambda function and so each lambda closure objects differs from each other. Thus, the asyncAt is templated to make the type of lambda available at runtime. There are three steps leading to the execution of a lambda remotely. First, the current place allocates memory in its partition of the global address space and copies the lambda object to it. Second, a UPC++’s async (asynchronous active message) taking the lambda as a parameter is invoked on the remote place. To ensure this UPC++ call is executed only by the communication worker (Section 4.2), the UPC++’s async is wrapped inside a lambda function and passed to the runtime. Third, the remote place processes the active message by executing the asyncAt_wrapper function which copies the lambda into the current place partition in the global address space and executes the lambda. On completion the reserved memory at both sender and destination place is deallocated. There is also some bookkeeping code to maintain the outgoing remote task count and incoming remote tasks count. They are explained in Section 4.3.

The implementation of asyncCopy is as shown in Figure 8. Similarly to asyncAt, asyncCopy is also scheduled to execute only at the communication worker and hence the UPC++’s async calls are wrapped inside a lambda function. Here the UPC++’s async_copy (asynchronous copy function) for remote copy is used. A callback function is also registered on this asynchronous copy, which gets invoked on the source place once the entire source data is copied to the destination buffer. Apart from the bookkeeping code, the callback is used to do a DDF_PUT if a DDF was supplied to the asyncCopy. It ensures that asyncAwait depending on those DDFs are notified when asyncCopy completes.

### 4.2 Integrating OCR with UPC++

We are using OCR (Section 2.2) as the Habanero-C++ workstealing runtime and UPC++ (Section 2.4) for global address space abstraction for memory management and data communications. HabaneroUPC++ asynchronous task relies on HClib (Section 2.3) to translate to an EDT (Event-Driven Task) representation, which can be passed to OCR for scheduling. In this section we discuss the modifications made to integrate OCR with UPC++. Figure 9 depicts different components of HabaneroUPC++ and shows how HabaneroUPC++ application’s executable is created.

We take the approach of Chatterjee et al. [7] and create a dedicated communication worker per HabaneroUPC++ place. Their experiments demonstrate that the benefits of a dedicated communication worker can outweigh the loss of parallelism from the inability to use it for computation. If OCR is configured to run on “n” cores then there will be one communication worker and “n-1” computation workers.

#### 4.2.1 Communication worker

Other than the usual work-stealing double-ended queue (deque), the communication worker also maintains a semi-concurrent deque. These are respectively named in_deque and out_deque. The in_deque allows for concurrent push and steal operations. The out_deque only allows concurrent push operations and non-concurrent pop operations. Having two separate deques allows easy identification of local and remote tasks when communication worker pops tasks for remote transfers and pushes tasks for local executions.

The communication worker is responsible for invoking the main function of the HabaneroUPC++ application. Whenever local asynchronous tasks (async, asyncAwait and asyncPhased) are created, they are pushed to its in_deque. Remote asynchronous tasks (asyncCopy and asyncAt) are pushed to its out_deque. When the end of a finish_npmd block or the main function is reached, the communication worker pops tasks from its out_deque and executes them. If a task is received from a remote place it is pushed in its in_deque. The details of how the communication worker uses UPC++ to send and receive a remote task are discussed in Section 4.3.

#### 4.2.2 Computation worker

When computation workers start, they have no tasks to execute and try to steal from other computation workers as well as the in_deque of the communication worker. Since the communication worker executes the main function, initially tasks are only available in its in_deque. Computation workers steal them from the in_deque and execute. These tasks can either be local or remote task. Whenever they encounter any local asynchronous tasks, they push it to their own deque. In case of remote asynchronous tasks, they always push to the out_deque of the communication worker and let the communication worker execute it. Hence, a push to out_deque is always potentially concurrent.

As an alternative to our current design, we can also allow a computation worker to start the main function rather than the commu-
We have used two benchmarks from UPC++ distribution and ported them to HabaneroUPC++. These benchmarks are briefly described below. Their detailed description is available in [39].

**SampleSort** It sorts a large distributed array of 64-bit integer keys. We are using weak scaling and the total keys per UPC++ *place* are $48 \times 1024 \times 1024$. The keys are generated using `rand()` function.

**LULESH** This is a shock hydrodynamics proxy application. This benchmark restricts the number of UPC++ *place* to a perfect cube of an integer. This benchmark is also using weak scaling. In our experiments the inputs to this benchmark are: the length of cube mesh along sides as 38 and total iteration count as 100.

### 5.1 Experimental Setup

#### 5.1.1 Benchmarks

We used Edison supercomputer at NERSC for our experimental evaluations. This is a Cray XC-30 system with Intel Ivy Bridge CPUs and an Aries interconnect with DragonFly topology. Each node has two sockets and each socket has 12 cores.

#### 5.1.2 Hardware Platform

We used Edison supercomputer at NERSC for our experimental evaluations. This is a Cray XC-30 system with Intel Ivy Bridge CPUs and an Aries interconnect with DragonFly topology. Each node has two sockets and each socket has 12 cores.

#### 5.1.3 Software Platform

**HabaneroUPC++** We have our runtime implementation and the benchmarks publicly available at:

http://habanero-rice.github.io/habanero-upc/

**OCR** Git version xstack-intel_2013-09-06-2-gd687b14.

**HClib** Git version v0.3-6-g62496d1.

**UPC++** Git version ver_0.1-51-g5f438c2.

**GCC** Version 4.9.0.

#### 5.1.4 Measurements

Once the nodes are allocated on the Edison, we run each experiment ten times. We report the execution time as the mean of these ten invocations along with a 95% confidence interval based on a Student t-test.

### 5.2 Results

#### 5.2.1 Work-Stealing Performance

Recall, HabaneroUPC++ uses Habanero-C++ work-stealing to achieve load-balance within a *place* and UPC++ to communicate across places. To measure the performance (weak scaling) of this programming model, we port our two benchmarks to HabaneroUPC++ and run them by varying total number of places and work-stealing workers. In this experiment (Figure 11) we launch one HabaneroUPC++ *place* per socket and vary the total number of work-stealing workers as 1, 4, 8 and 12 at each place. Y-axis represents the performance and X-axis shows total number of places. Both the axes are in log-scale.

The UPC++ version of SampleSort uses `qsort` function from C++’s `<cstdlib>` header file for local sort of keys. There are total of three such occurrences of `qsort` functions. For porting to HabaneroUPC++ we take the default version of SampleSort and replace all the three `qsort` with a parallel divide and conquer implementation. This modified `qsort` uses `asyncAt` to parallelize each of the sub-problems and `finish` to join all these `async`. A threshold of 5120 is used to control the task granularity. This benchmarks also uses one `asyncCopy` to distribute and copy the array across the places. There is no `asyncCopy` in the benchmark. `finish_spmd` is
```cpp
void finish_spmd(std::function<void()> lambda) {
    // Start finish scope
    allocate_finish_object();
    // Execute the lambda containing
    // asynchronous tasks.
    lambda();
    // Loop until no more pending tasks
    // at global scope (both local and
    // remote)
    while(true) {
        // Pop and execute tasks from out_deque
        while(true) {
            void* task = pop_out_deque();
            if(task == NULL) break;
            else {
                // Execute lambda function in the task.
                // This lambda contains UPC++ calls ,
                // details in Figure 7 and 8.
                async_wrapper(lambda); // see Figure 6
            }
        }
    }
    // Send and receive remote tasks in
    // UPC++ queue
    void* incoming_remoteTask = advance_upcxx();
    if(incoming_remoteTask != NULL) {
        // Wrap it as local async which will
        // push this task to in_deque
        async([=]() {
            // Call UPC++ library to execute this task.
            execute_upcxx(incoming_remoteTask);
        });
    }
    // Find total global pending tasks
    allreduce(&tasks_count, &global_tasks_count, SUM);
    if(global_tasks_count==0) break;
}
// end finish scope
free_finish_object();
// end finish_spmd
```

Figure 10: Runtime implementation of finish_spmd

Figure 11: Weak scaling performance using HabaneroUPC++ and varying number of work-stealing worker threads per place.

Figure 12: Performance comparison of HabaneroUPC++ with UPC++. 
used to join the \texttt{asyncCopy} task. The result of this experiment is shown in Figure 11(a). The performance of the benchmarks is represented on y-axis as total terabytes sorted per second (TB/sec). As we can see, increasing the total number of work-stealing worker threads increases the performance. We noticed an improvement of $3.4 \times$ by increasing the worker threads count from 1 to 12 with 512 places.

The UPC++ version of LULESH has several for-loops. We modify the default LULESH to use \texttt{forasync} instead of for-loops. The \texttt{forasync} tasks are joined with the help of \texttt{finish}. Default LULESH also uses UPC++ version of asynchronous copy and its own wait function. We modify LULESH to use our \texttt{asyncCopy} and \texttt{finish_spmd} to join them. There are total 3 such modifications. This benchmark too does not use \texttt{asyncAt}. The result of this experiment is shown in Figure 11(b). The performance of LULESH (FOM – zones per second) is presented on y-axis. We noticed consistent improvement of $2 \times$ by increasing the number of work-stealing worker threads count from 1 to 12 at all places.

5.2.2 HabaneroUPC++ Performance versus UPC++

The performance comparison of the HabaneroUPC++ version of benchmarks with the UPC++ version is shown in Figure 12. Y-axis shows the performance and X-axis shows the total number of cores used across each implementation. Both the axes are in log-scale.

For SampleSort benchmark, in the HabaneroUPC++ version we compare the performance of $P$ places, each running with 12 work-stealing workers (total $12 \times P$ execution units) against the UPC++ version running with $12 \times P$ places. To ensure same computation size (weak scaling) across both versions, HabaneroUPC++ uses total keys per place as $12 \times N$ whereas UPC++ uses $1 \times N$ ($N = 4 \times 1024 \times 1024$). The result of this experiment is shown in Figure 12(a). Similar experimental setup is not viable for LULESH. In the HabaneroUPC++ version of LULESH we compare the performance of $P$ places, each running with 1 work-stealing worker (total $1 \times P$ execution units) against the UPC++ version running with $P$ places. The result of this experiment is shown in Figure 12(b).

The HabaneroUPC++ version of SampleSort performs nearly identical to UPC++. However, UPC++ version of LULESH consistently performs 20% better than HabaneroUPC++ version. This slight gap in performance is due to the overheads of work-stealing and heap allocation of C++11 lambda objects. Prior studies have shown that work-stealing overheads can be minimized by tweaking the compilers [34, 17]. As future work, we would like to develop similar techniques for Habanero-C++ work-stealing runtime. We would also like to include irregular benchmarks for performance study. Irregular applications pose significant challenges to achieving scalable performance on large-scale multicore clusters. These applications require dynamic load balancing to maintain efficiency. Prior studies have demonstrated that work-stealing implementations can provide very effective load-balancing for these kinds of applications [9, 8]. We predict that HabaneroUPC++ can definitely provide better performance for these irregular applications.

6. RELATED WORK

C++11 brings rich support for threading. It provides a function template \texttt{std::async}. This \texttt{async} takes callable object (or function) as an argument and returns a \texttt{std::future} object. This \texttt{async} can execute asynchronously. The user can use a \texttt{get()} function over the \texttt{std::future} object to wait for the \texttt{async} to complete and fetch the result of function execution. Habanero-C++ \texttt{async} differs greatly from C++11 \texttt{async}. Other than providing 3 different varieties of \texttt{async}, Habanero-C++ also allows arbitrary nesting of \texttt{async}. The user can join all the \texttt{async} using a single \texttt{finish}. Another great feature provided by C++11 is lambda functions. We are unaware of any C++ based dynamic tasking library which uses lambda functions as we do. Habanero-Java library [15] is a very recent, pure Java 8 library implementation of Habanero constructs. User interfaces to Habanero constructs are very similar across both Habanero-Java and Habanero-C++. However, the runtime implementations are very different. Being a C++ implementation, Habanero-C++ has the advantage that it can be combined with any C++ based high performance libraries.

Work-stealing is a very popular technique for load-balancing of dynamically spawned tasks and is used extensively. Chatterjee et al. designed HCMPI runtime, which is an integration of Habanero-C (Section 2.1) with MPI [7]. HCMPI unifies asynchronous task parallelism at intra-node level with MPI’s message passing model at the inter-node level. However, by using MPI it’s not able to harness the benefits of PGAS programming model. It’s able to tie only the remote message transfer with the Habanero-C’s \texttt{finish}\texttt{-async} constructs. By using a PGAS approach, HabaneroUPC++ offers better productivity and also provides asynchronous remote function shipping along with asynchronous remote copy. HCMPI requires complex compiler transformations unlike HabaneroUPC++. The approach of using a dedicated communication worker is similar in both HabaneroUPC++ and HCMPI, but HCMPI communication worker does not uses two deques as in HabaneroUPC++.

X10 and Chapel are very recent PGAS implementations. X10 introduced \texttt{finish-async} style programming model and uses work-stealing scheduling for load-balancing [32, 31, 38]. Both X10 and Chapel rely on compiler transformations to map user code to native code. Being a new programming language they are currently not as popular as C++. HabaneroUPC++ takes the C++ approach and adds \texttt{finish-async} style asynchronous tasking to SPMD PGAS programming model. By using C++11 lambda functions, HabaneroUPC++ avoids complex compiler transformations while retaining the elegance of language constructs. Unlike X10, HabaneroUPC++ currently does not support distributed work-stealing. The \texttt{finish_spmd} function in HabaneroUPC++ library is very similar to \texttt{FINISH_SPMD} pragma in X10 [31], although its implementation differs.

Min et al. introduced API based task library for using dynamic tasking in UPC [21]. The idea of favoring work-stealing inside PGAS programming model is similar across both Min et al. and HabaneroUPC++. However, there are several differences in the implementations. Some of them are: a) API based task library lacks the productivity of \texttt{finish-async} programming model; b) \texttt{finish-async} allows arbitrary nesting of both \texttt{finish} and \texttt{async} and provides more control to the programmer; and c) HabaneroUPC++ not just allow dynamic tasking but also allows creating dependencies among asynchronous tasks (\texttt{asyncAwait} and \texttt{asyncPhased}).

7. CONCLUSION

In this paper we presented HabaneroUPC++, a C++11 lambda functions-based compiler-free PGAS library. This library integrates Habanero’s intra-place dynamic tasking constructs with UPC++’s inter-place asynchronous remote copy and asynchronous function shipping features. We also present a \texttt{finish} implementation for joining both local and remote asynchronous tasks. By using C++11 lambda functions we retain the syntactic convenience of language-based approaches while avoiding their associated complexities. Our intra-place work-stealing runtime uses a combination of communication and computation worker threads to enable the integration of the two programming models. We have presented a design based on a single communication worker run-
ning at each place that is responsible for managing the traffic of all the inter-place asynchronous tasks. This design allows the computation workers to execute both the local tasks as well as the tasks received from remote places. We have evaluated HabaneroUPC++ on Edison supercomputer at NERSC by using two benchmarks. We have scaled the benchmarks up to 6k cores and vary the total number of work-stealing worker threads at each place to demonstrate the performance and productivity of HabaneroUPC++.

There are several exciting future directions for this work. Some of them are a) distributed work-stealing implementation; b) extending the performance evaluation to a wider variety of benchmarks; c) a study of the limitations and overhead of using C++11 lambda functions and techniques to overcome them; and d) implementation of a non-SPMD (X10 style) HabaneroUPC++ and comparison with the SPMD approach.

8. REFERENCES