UPC++: A High-Performance Communication Framework for Asynchronous Computation

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UPC++: a C++ PGAS Library

• Global Address Space (PGAS)
  - A portion of the physically distributed address space is visible to all processes. Now generalized to handle GPU memory

• Partitioned (PGAS)
  - Global pointers to shared memory segments have an affinity to a particular rank
  - Explicitly managed by the programmer to optimize for locality
Why is PGAS attractive?

• The overheads are low
  Multithreading can’t speed up overheads
• Memory-per-core is dropping, requiring reduced communication granularity
• Irregular applications exacerbate granularity problem

Asynchronous computations are critical

• Current and future HPC networks use one-sided transfers at their lowest level and the PGAS model matches this hardware with very little overhead
What does UPC++ offer?

- Asynchronous behavior based on futures/promises
  - **RMA**: Low overhead, zero-copy one-sided communication. Get/put to a remote location in another address space
  - **RPC**: Remote Procedure Call: invoke a function remotely. A higher level of abstraction, though at a cost

- Design principles encourage performant program design
  - All communication is syntactically explicit (unlike UPC)
  - All communication is asynchronous: futures and promises
  - Scalability

Remote procedure call (RPC)

Global address space (Shared segments)

One sided communication

Private memory
How does UPC++ deliver the PGAS model?

• A “Compiler-Free” approach
  - Need only a standard C++ compiler, leverage C++ standards
  - UPC++ is a C++ template library

• Relies on GASNet-EX for low overhead communication
  - Efficiently utilizes the network, whatever that network may be, including any special-purpose offload support

• Designed to allow interoperation with existing programming systems
  - 1-to-1 mapping between MPI and UPC++ ranks
  - OpenMP and CUDA can be mixed with UPC++ in the same way as MPI+X
A simple example of asynchronous execution

By default, all communication ops are split-phased
- **Initiate** operation
- **Wait** for completion

A future holds a value and a state: ready/not ready

```
global_ptr<T> gptr1 = ...;
future<T> f1 = rget(gptr1);
// unrelated work..
T t1 = f1.wait();
```

Wait returns with result when rget completes
Simple example of remote procedure call

Execute a function on another rank, sending arguments and returning an optional result

1. Injects the RPC to the target rank
2. Executes \( \text{fn}(\text{arg1}, \text{arg2}) \) on target rank at some future time determined at the target
3. Result becomes available to the caller via the future

Many invocations can run simultaneously, hiding data movement

```
upcxx::rpc(target, fn, arg1, arg2 )
```

Execute \( \text{fn}(\text{arg1}, \text{arg2}) \) on rank target
Asynchronous operations

• Build a DAG of futures, synchronize on the whole rather than on the individual operations
  - Attach a callback: `.then(Foo)`
  - `Foo` is the completion handler, a function or λ
    • runs locally when the `rget` completes
    • receives arguments containing result associated with the future

```cpp
double Foo(int x){ return sqrt(2*x); }
global_ptr<int> gptr1;
// ... gptr1 initialized
future<int> f1 = rget(gptr1);
future<double> f2 = f1.then(Foo);
// DO SOMETHING ELSE
double y = f2.wait();
```
A look under the hood of UPC++

- Relies on GASNet-EX to provide low-overhead communication
  - Efficiently utilizes the network, whatever that network may be, including any special-purpose support
  - Get/put map directly onto the network hardware’s global address support, when available
- RPC uses an active message (AM) to enqueue the function handle remotely.
  - Any return result is also transmitted via an AM
- RPC callbacks are only executed inside a call to a UPC++ method (Also a distinguished progress() method)
  - RPC execution is serialized at the target, and this attribute can be used to avoid explicit synchronization

https://gasnet.lbl.gov
RMA microbenchmarks

Experiments on NERSC Cori:
- Cray XC40 system

- Two processor partitions:
  - Intel Haswell (2 x 16 cores per node)
  - Intel KNL (1x68 cores per node)

Data collected on Cori Haswell

Round-trip Put Latency (lower is better)

Flood Put bandwidth (higher is better)

Data collected on Cori Haswell
Distributed hash table – Productivity

- Uses Remote Procedure Call (RPC)
- RPC simplifies the distributed hash table design
- Store value in a distributed hash table, at a remote location

```cpp
// C++ global variables correspond to rank-local state
std::unordered_map<std::string, std::string> local_map;
// insert a key-value pair and return a future
future<> dht_insert(const string & key, const string & val) {
    return upcxx::rpc(get_target(key),
        [](string key, string val) {
            local_map.insert ({key, val});
            }, key, val);
}
```
Distributed hash table – Performance

- RPC+RMA implementation, higher performance (zero-copy)
- RPC inserts the key at target and obtains a landing zone pointer
- Once the RPC completes, an attached callback (.then) uses zero-copy rput to store the associated data
- The returned future represents the whole operation

```
1. rpc(get_target(key), F, key, len )

2. F: Allocates landing zone for data of size len
   Stores (key,gptr) in local hash table (remote to sender)
   Returns a global pointer loc to landing zone

3. rpc completes:
   fut.then(return rput(val.c_str(),
                   loc,val.size()+1))
```

Hash table partition: a std::unordered_map per rank

Global address space
Private memory
The hash table code

```cpp
#include <unordered_map>

std::unordered_map<std::string, global_ptr<char>> local_map;

future<> dht_insert(const string &key, const string &val) {
    auto f1 = rpc(get_target(key), // RPC obtains location for the data
                   [](string key, size_t len) -> global_ptr<char> {
                       global_ptr<char> gptr = new_array<char>(len);
                       local_map[key] = gptr; // insert in local map
                       return gptr;
                   }, key, val.size()+1);
    return f1.then( // callback executes when RPC completes
                    [val](global_ptr<char> loc) -> future<> { // : RMA put
                        return rput(val.c_str(), loc, val.size()+1); }
                    );
}
```

Mathias Jacquelin / UPC++ / IPDPS 2019 / upcxx.lbl.gov
Weak scaling of distributed hash table insertion

- Randomly distributed keys
- Excellent weak scaling up to 32K cores
- RPC leads to simplified and more efficient design
- RPC+RMA achieves high performance at scale

NERSC Cori Haswell
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UPC++ improves sparse solver performance

- Sparse matrix factorizations have low computational intensity and irregular communication patterns
- **Extend-add** operation is an important building block for **multifrontal** sparse solvers
- Sparse factors are organized as a hierarchy of condensed matrices called **frontal matrices**:
  - 4 sub-matrices:
    - factors + contribution block
  - Contribution blocks are accumulated in parent
UPC++ improves sparse solver performance

- Data is packed into per-destination contiguous buffers
- Traditional MPI implementation uses MPI_Alltoallv
  - Variants: MPI_Isend/MPI_Irecv + MPI_Waitall / MPI_Waitany
- UPC++ Implementation:
  - RPC sends child contributions to the parent
  - RPC compare indices and accumulate contributions on the target
UPC++ improves sparse solver performance

Run times for audikw_1

Assembly trees / Frontal matrices extracted from STRUMPACK
UPC++ improves sparse solver performance

Run times for audikw_1

Assembly trees / Frontal matrices extracted from STRUMPACK
UPC++ = Productivity + Performance

Productivity

• UPC++ does not prescribe solutions for implementing distributed irregular data structures: it provides building blocks
• Interoperates with MPI, OpenMP and CUDA
• Develop incrementally, enhance selected parts of the code

Reduced communication costs

• Embraces communication networks that use one-sided transfers at their lowest level
• Low overhead reduces the cost of fine-grained communication
• Overlap communication via asynchrony and futures
• High-performance distributed hash table
• Increased efficiency in the extend-add operation (sparse solvers)

More advanced constructs (not discussed)

• Remote atomics, distributed objects, teams and collectives
• Promises, end points, generalized completion
• Serialization, non-contiguous transfers
The Pagoda Team

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Examples and extras available at the end of May
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http://upcxx.lbl.gov

Figure courtesy Alexander Pöppl
Additional information
Related work on PGAS

• UPC, Fortran 2008 coarrays, OpenSHMEM, Titanium
• Fork-join model: X10, Chapel
• DASH / DART (over MPI-3 RMA backend)
• Coarray C++

• Task-based models: HPX, Phalanx, Charm++, HabaneroUPC++
Differences with legacy UPC++ v0.1

- Both implement PGAS model
- Different APIs:
  - Current version avoids:
    - Implicit communication
    - Non-scalable data structures
  - Current version based on futures/promises (similar to C++11)
  - Leg. version uses `async/finish` syntax (like X10,Habanero-C)
- New functionalities:
  - Futures encapsulate values, events do not
  - Futures allow to attach callbacks
  - Easier to manage future’s lifetime vs. event
  - RPCs can return a value, asyncs cannot
Upc++ v1.0 vs. v0.1 performance

- SymPACK, supernodal solver for symmetric sparse matrices
- Implementation based on RPC & RMA
- Outperforms state-of-the-art solvers implemented using MPI

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Where does message passing overhead come from?

• Matching sends to receives
  - Messages have an associated context that needs to be matched to handle incoming messages correctly
  - Data movement and synchronization are coupled

• Ordering guarantees are not semantically matched to the hardware

• UPC++ avoids these factors that increase the overhead
  - No matching overhead between source and target
  - Executes fewer instructions to perform a transfer