SC21
St. Louis, MO | science & beyond.

Optimization of Asynchronous Communication Operations through Eager Notifications

Amir Kamil and Dan Bonachea

Applied Mathematics and Computational Research Division
Lawrence Berkeley National Laboratory
https://upcxx.lbl.gov/

Paper: doi:10.25344/S42C71 Video: doi:10.25344/S4JC7C

UPC++ overview

UPC++ uses a “Compiler-Free,” library approach

- UPC++ leverages C++ standards,
  needs only a standard C++ compiler

GASNet-EX

Relies on GASNet-EX for low-overhead communication

- Efficiently utilizes network hardware, including RDMA
- Provides Active Messages on which UPC++ RPCs are built
- Enables portability (laptops to supercomputers)

Designed for interoperability

- Same process model as MPI, enabling hybrid applications
- OpenMP and CUDA can be mixed with UPC++ as in MPI+X

What does UPC++ offer?

Asynchronous behavior

- **RMA: Remote Memory Access**:
  - Get/put/accumulate to a location in another address space
  - Low overhead, zero-copy, one-sided communication
- **RPC: Remote Procedure Call**:
  - Moves computation to the data

Design principles for performance

- All communication is syntactically explicit
- All communication is asynchronous: futures and promises
- Scalable data structures that avoid unnecessary replication

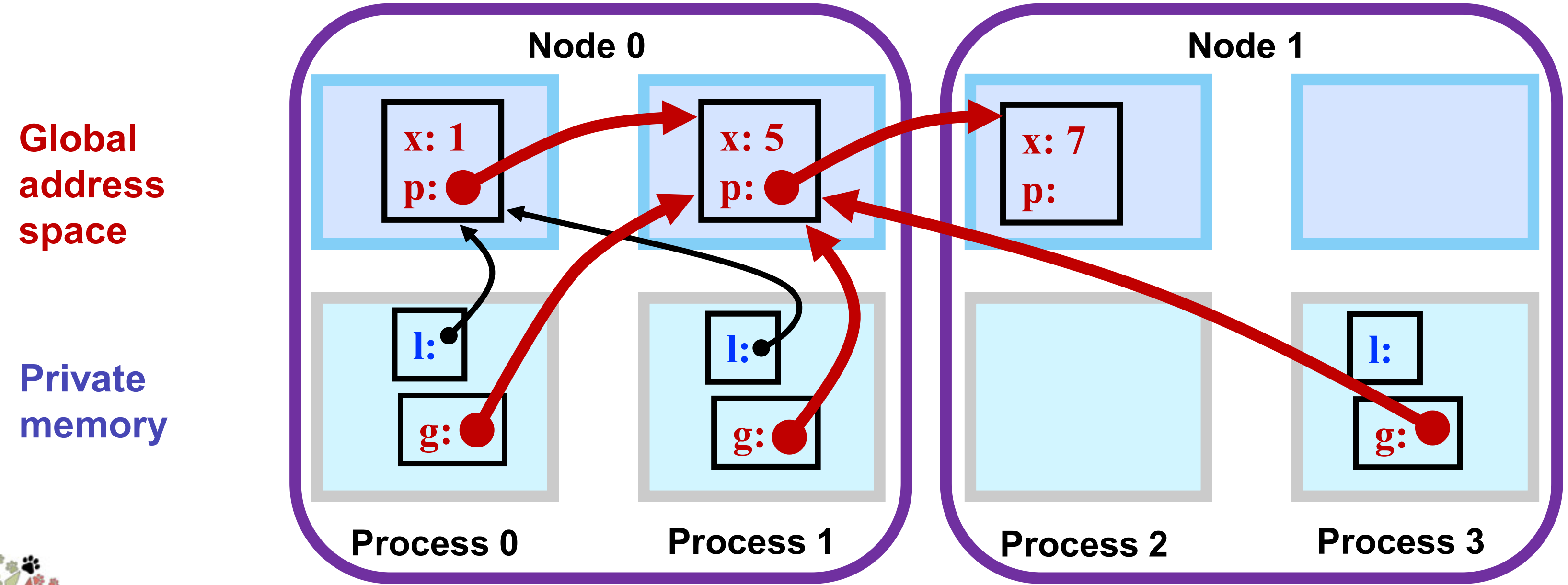
A Partitioned Global Address Space programming model

Global Address Space

- Processes may read and write *shared segments* of memory
- Global address space = union of all the shared segments

Partitioned

- *Global pointers* to objects in shared memory have an affinity to a particular process
- Explicitly managed by the programmer to optimize for locality

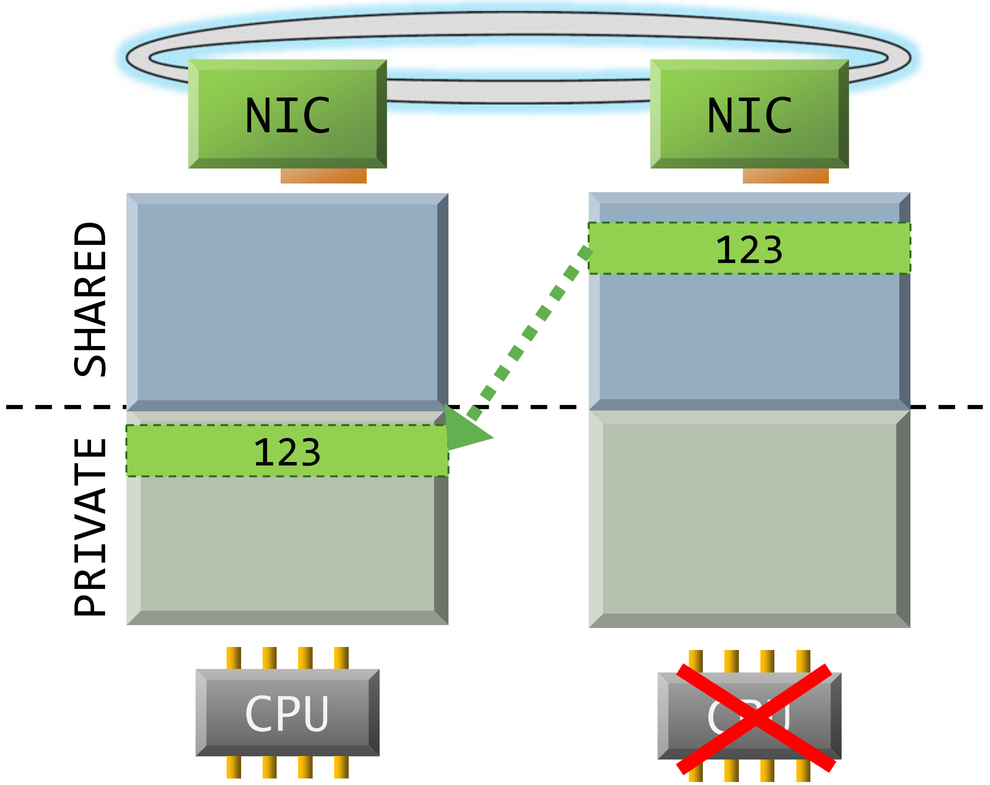


Asynchronous RMA in UPC++

By default, all communication operations are split-phased

- **Initiate** operation
- **Wait** for completion

```
upcxx::global_ptr<int> gptr1 = ...;
upcxx::future<int> f1 =
                   upcxx::rget(gptr1);
// unrelated work...
int t1 = f1.wait();
upcxx::future<> f2 =
                   upcxx::rput(42, gptr1);
```



A UPC++ future holds values and a state: ready/not-ready

`wait` returns the result when the `rget` completes

Aggressive asynchrony via futures and callbacks

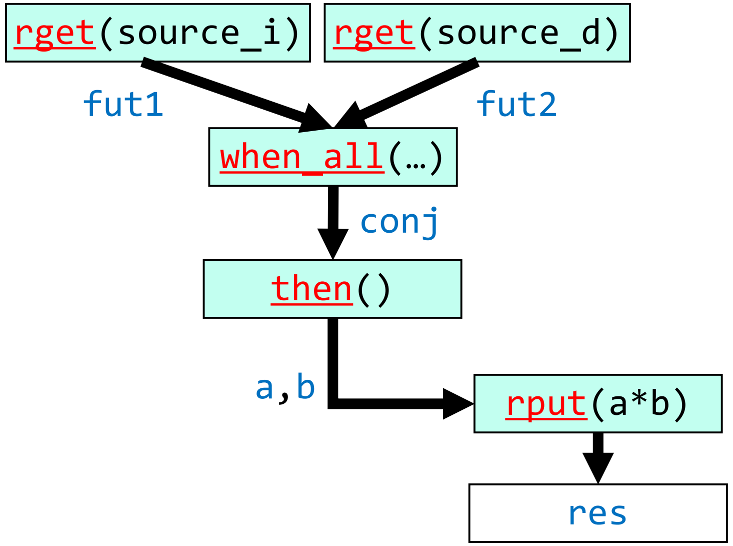
RMA returns a *future* object, which represents an operation that may or may not be complete

Callbacks can be *chained* through calls to `then()`

Multiple futures can be *conjoined* with `when_all()` into a single future that encompasses all their results.

This code gets two remote values (an `int` and a `double`) and puts their product to another location:

```
global_ptr<int>      source_i = ...;
global_ptr<double>   source_d = ...;
global_ptr<double>   target   = ...;
future<int>          fut1 = rget(source_i);
future<double>       fut2 = rget(source_d);
future<int, double> conj = when_all(fut1, fut2);
future<> res = conj.then([target](int a, double b) {
                    return rput(a*b, target);
                 });
```



Completion: synchronizing communication

Communication can be synchronized using futures:

```
future<int> fut = rget(remote_gptr);
int result = fut.wait();
```

This is just the default form of synchronization

- Most communication ops take a defaulted completion argument
- More explicitly: `rget(gptr, operation_cx::as_future());`
  - Requests future-based notification of operation completion

Other completion arguments may be passed to modify behavior

- Can trigger different actions upon completion, e.g.:
  - Signal a promise (the producer side of a future), deliver an RPC, etc.
- Can even combine several completions for the same operation

Progress and deferred notifications

UPC++ does not spawn hidden threads to advance its internal state or track asynchronous communication

- Keeps the runtime lightweight and simplifies synchronization

Prior releases (2021.3.0 and earlier) required completion notifications to be deferred until the next call into the progress engine

- Provides consistent behavior for code such as:

```
global_ptr<int> gptr = producer();
future<> f1 = rput(42, gptr);
future<> f2 = f1.then(... /* code block #1 */);
/* code block #2 */
f2.wait();
```

- Ensures that code block #2 executes before code block #1

Downsides of deferred notifications

Deferred notification can incur significant overheads for on-node accesses

- Future-based notification must allocate a promise cell on the heap, schedule it to be fulfilled later

Programmers often do manual localization to avoid this:

```
global_ptr<double> gptr = ...;
if (gptr.is_local()) {
  *(gptr.local()) = 42; // direct load/store access
  // do overlappable computation
} else {
  future<> fut = rput(42, gptr);
  // do overlappable computation
  fut.wait();
}
```

- Leads to code bloat, duplicates locality check that is already in the runtime

Eager notifications

New eager notification added in 2021.3.6 snapshot, included in most recent 2021.9.0 release

- Immediately signals notification for synchronous completion

New factory methods for requesting deferred or eager notification:

```
operation_cx::as_defer_future()
operation_cx::as_eager_future()
operation_cx::as_defer_promise(promise<T...> &p)
operation_cx::as_eager_promise(promise<T...> &p)
```

New macro to control whether `as_future` and `as_promise` request eager or deferred notification

- If not defined, defaults to eager

Optimization of ready futures

Ready futures that do not encapsulate a value (i.e. `future<>`) are semantically equivalent with each other

- Implementation optimized to use common, pre-allocated internals

When conjoining multiple futures, if the resulting values and readiness only come from a single future, the result is semantically equivalent to that one input future

```
future<int, double> fut1 = ... /* not ready */;
future<> fut2 = ... /* ready */, fut3 = ... /* ready */;
auto result = when_all(fut1, fut2, fut3);
```

Optimizations significantly improve performance of loops that conjoin many operations when most complete synchronously

```
future<> f = make_future();
for (int i = 0; i < 10; ++i)
  f = when_all(f, rput(i, gptrs[i]));
```

Evaluation

Three versions of UPC++:

- 2021.3.0 release – most recent release prior to this work, used as control
- 2021.3.6 snapshot with deferred notifications
- 2021.3.6 snapshot with eager notifications

Benchmarks:

- Microbenchmarks: RMA and atomics
- GUPS: HPC Challenge RandomAccess benchmark
- Graph Matching: half-approximate maximum-weight matching

Experiments run on 3 systems on a single node, with 16 processes

- Only Intel Skylake results shown here; similar results on IBM Power9 and Marvell ThunderX2 (see paper)

Microbenchmarks

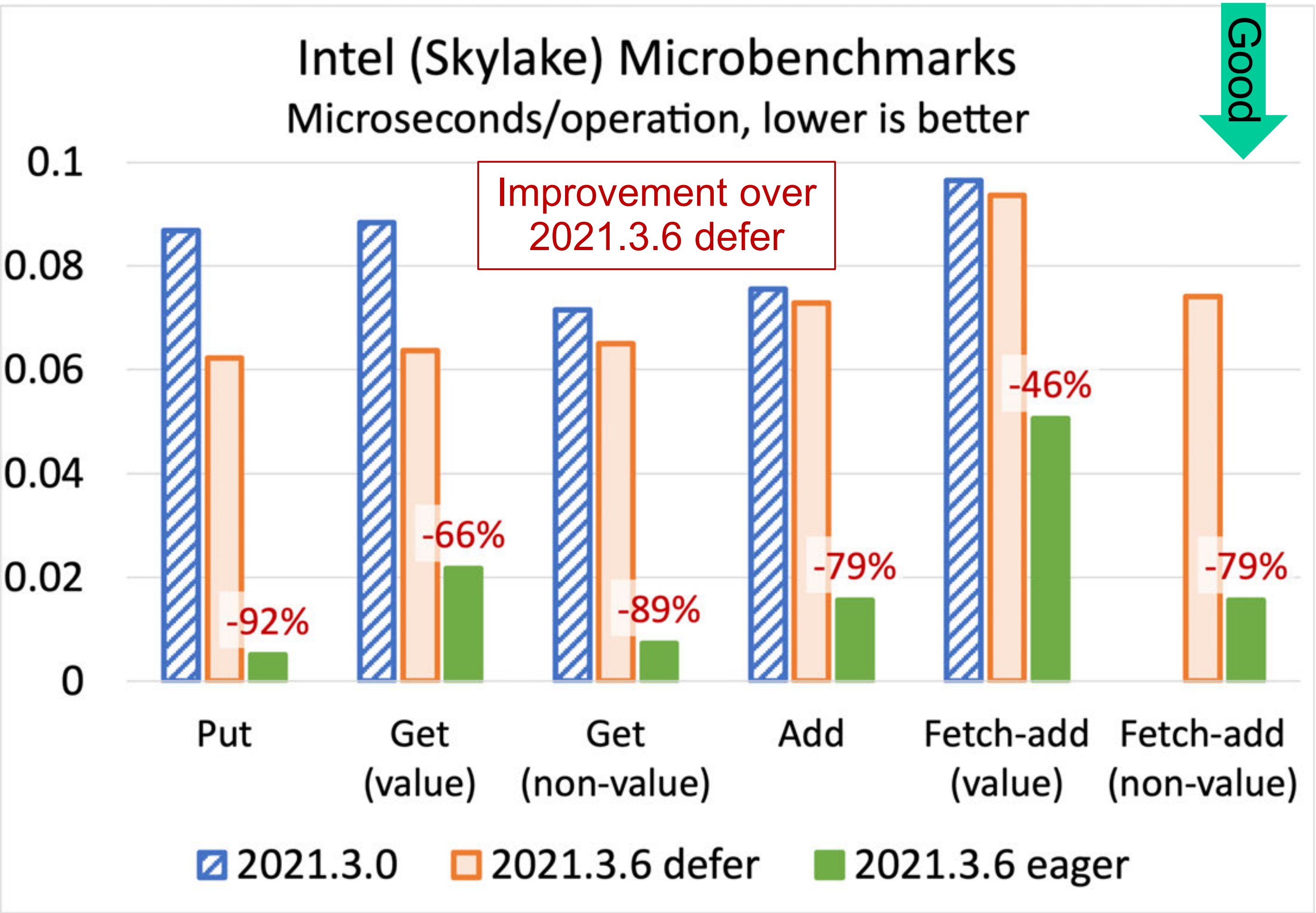
RMA or atomic transfers of 64-bit data between co-located processes

Each experiment timed 10M operations, initiating and then immediately waiting on each one

Average over 10 experiments

Observations:

- No performance regression between 2021.3.0 and 2021.3.6
- Eager is 46-92% faster than defer



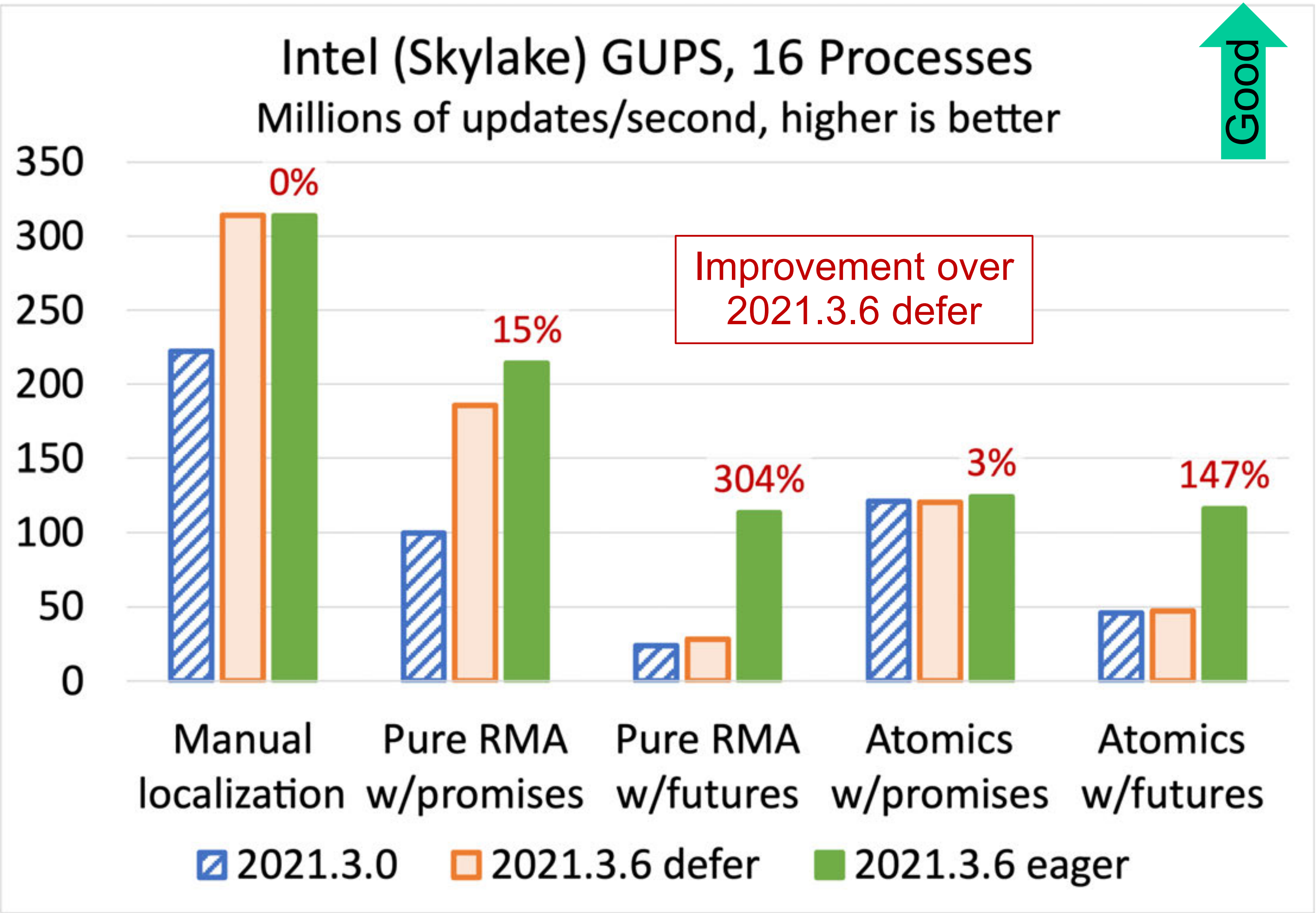
GUPS

Randomized fine-grained updates on distributed table

Several versions, using RMA or atomics, with future or promise notification

Observations:

- Eager is 3-15% faster than defer when using promises
- 147-304% faster when using futures due to skipping the progress engine as well as improvements to conjoining ready futures



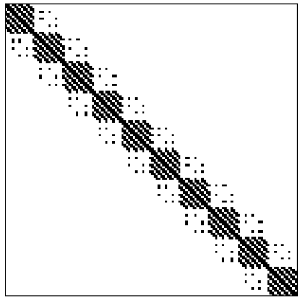
Graph matching

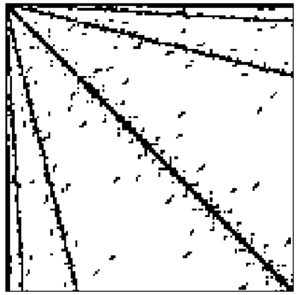
Half-approximate maximum-weight matching from ExaGraph developers

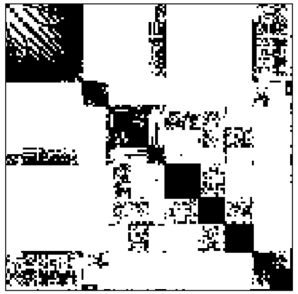
Code optimizes updates to same process, but not to co-located processes

Experiments with four sparse graphs with varying degrees of locality from SuiteSparse Matrix Collection[1]:

- Channel
- Delaunay
- Venturi
- Youtube







Additional graph randomly generated from the application itself, with ~13% of the edges between random vertices

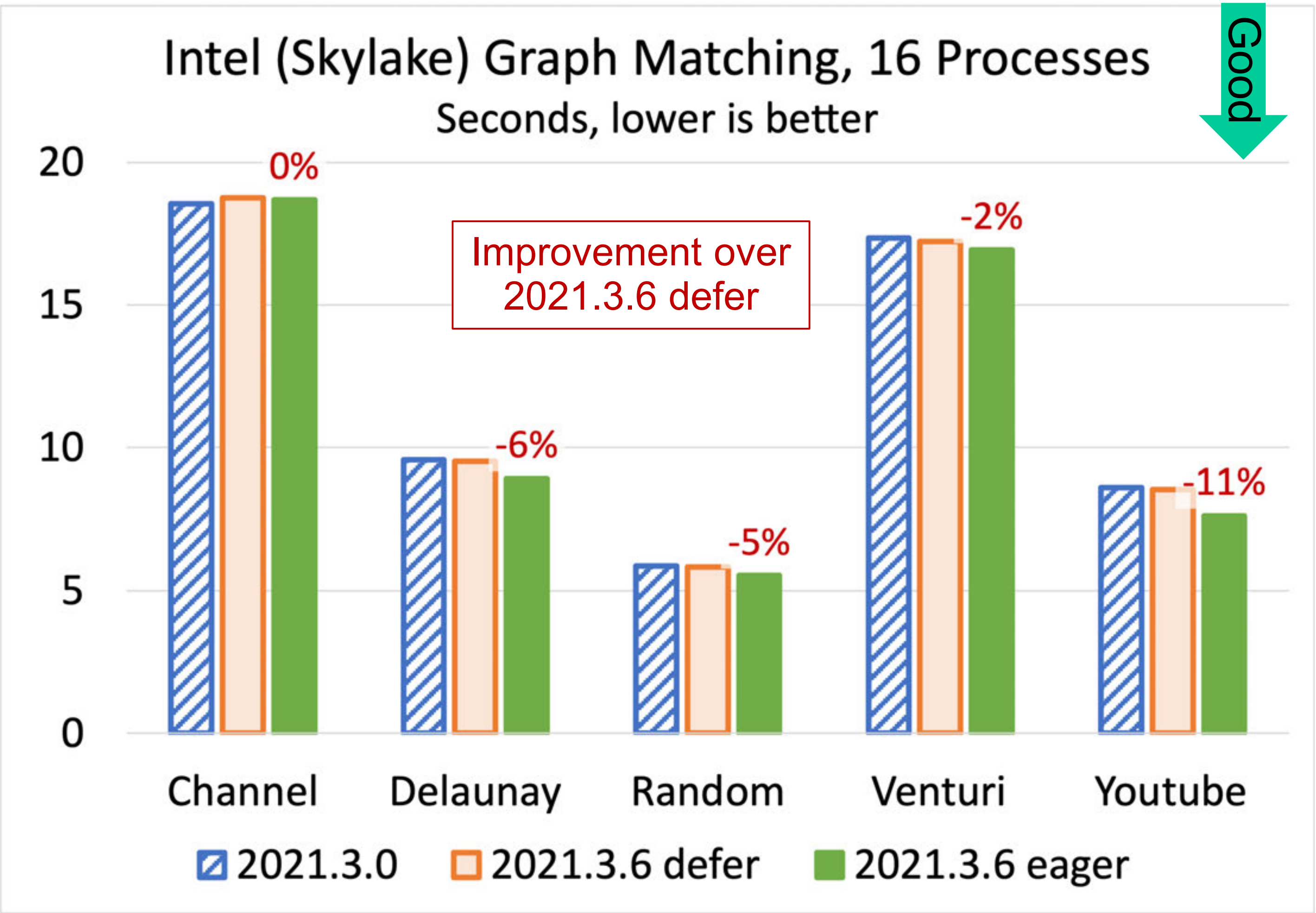
[1] Timothy A. Davis and Yifan Hu. 2011. The University of Florida Sparse Matrix Collection. ACM Transactions on Mathematical Software 38, 1, Article 1 (December 2011), 25 pages. DOI: https://doi.org/10.1145/2049662.2049663. Graphs and images obtained from https://sparse.tamu.edu.

Graph matching results

RMA-based UPC++ implementation by Sayan Ghosh (mel-upx)

Observations:

- Speedup limited by how much of the time is spent in communication, and what fraction is between different processes
- ~5% improvement for graphs with medium locality, 11% for graph with higher fraction of updates to co-located processes



Conclusions

The PGAS model enables the same code to operate on both on-node and off-node memory

- Provides productivity and maintainability

Asynchronous PGAS systems need to ensure that mechanisms for asynchrony only minimally impact performance of on-node operations

For UPC++, eager notifications provide significantly better performance than deferred notifications for on-node operations

- Up to 10x speedup for microbenchmarks, 3x for GUPS, 1.11x for graph matching on Intel Skylake
- Even higher speedups on other platforms (see paper)

Ongoing work in UPC++ to further optimize on-node operations

Acknowledgements

This research was supported in part by the **Exascale Computing Project** (17-SC-20-SC), a collaborative effort of two U.S. Department of Energy organizations (Office of Science and the National Nuclear Security Administration) responsible for the planning and preparation of a capable exascale ecosystem, including software, applications, hardware, advanced system engineering and early testbed platforms, in support of the nation's exascale computing imperative.

This research used resources of the **National Energy Research Scientific Computing Center (NERSC)**, a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231, as well as This research used resources of the **Oak Ridge Leadership Computing Facility** at the Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

Thank you!