Benchmarks and Performance Optimizations

Chapel Team, Cray Inc.
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Outline

● **ugi Improvements**
  ● ISx Background
  ● Block Transfer Engine (BTE)
  ● Active Message (AM) improvements

● **Communication Optimizations**
  ● locale.id Communication
  ● Barrier Optimizations

● **Qthreads Improvements**
  ● Sync Variable Serialization
  ● Parallel I/O Improvements
  ● Other Sync Variable Improvements

● **Bale Case Study**
  ● Histogram Mini-App
    ● Background
    ● Faster Blocking Atomics
    ● Buffered Atomics

● **Memory Leak Improvements**
ugi Improvements
ISx Background
ISx: Background

● **Scalable Integer Sort benchmark**
  ● Developed at Intel, published at PGAS 2015
  ● SPMD-style computation with barriers
  ● Punctuated by all-to-all bucket-exchange pattern
    ● buckets being exchanged are relatively large (100’s of MBs)
  ● References implemented in SHMEM and MPI

● **Chapel implementation introduced in 1.13 release**
  ● Motivation: bucket-exchange is a common distributed pattern
  ● Benchmark has led to several previous optimizations
    ● fast/scalable slicing, bulk transfer optimizations, barrier improvements, …
**ISx: Background**

- **ISx performance still lagged behind reference SHMEM**
  - Chapel scaled well, but raw performance was up to ~30% behind
ugni: Block Transfer Engine (BTE)
BTE: Background and This Effort

**Background:** comm=ugni only used Fast Memory Access (FMA)
- FMA is optimized for small transfers
- uGNI library also supports Remote Direct Memory Access (RDMA)
  - RDMA is initiated through the Block Transfer Engine (BTE)
  - BTE is optimized for large transfers

**This Effort:** Use BTE for PUTs/GETs larger than 4KB
- This significantly increases sustained bandwidth for larger transfers
- 4KB threshold chosen based on tuning, and matches GASNet
BTE: Impact

- Significantly increased sustained transfer bandwidth
  - Transfers larger than 1MB can sustain max hardware injection rate
  - on par with gasnet-aries, which already used BTE for large transfers
BTE: ISx Impact

- ISx performance now on par with reference
- No known next steps
ugi: Active Message (AM) Improvements
AM Improvements: Background

- FFT regressions in 1.17 from “AM done” indicator change
  - AM done indicators are used to track whether an AM has completed
  - Changed from stack-allocated to heap-allocated pool
    - stack-allocated: cheap allocation, but requires memory registration lookup
    - heap-allocated: contended allocation, but no registration lookup required
AM Improvements: This Effort and Impact

**This Effort:** Revert to stack-allocated AM done indicators
- Allocation contention outweighs registration lookup cost

**Impact:** FFT performance is better, though still behind 1.16
- Remaining hit is from switch to blocking progress thread in 1.17.1
  - needed to mitigate performance hit from Spectre/Meltdown patches
Communication Optimizations
locale.id Communication
Background: .id method on a locale returns the locale number

- Useful for data structures reasoning about locality

  // Suppose A is block distributed and we want to aggregate updates to it.
  for indexToUpdate in 1..1000 {
    const dstLocale = A.domain.dist.idxToLocale(indexToUpdate);
    addUpdate(dstLocale.id, indexToUpdate);
  }

- However dstLocale.id was causing unnecessary communication

This Effort: Removed the unnecessary communication

- Fix suggested by Louis Jenkins

Impact: Surprising source of communication eliminated

- above example now has 0 GETs instead of thousands
- enables progress on prototype aggregation library
Barrier Optimizations
Barrier Optimizations

**Background:** Barrier implementation is not very scalable
- Scalable `allLocalesBarrier` added in 1.17
- but the more flexible and default barrier has not been tuned for scale

**This Effort:** Optimize barriers under network atomics

**Impact:** Performance improvements for network atomic barrier

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**Next Steps:** Continue to tune default barrier
Qthreads Improvements
Qthreads: Sync Variable Serialization
Sync Var: Background

● Users ran into perf bottlenecks using sync vars as locks
  ● Example from “Parallel Sparse Tensor Decomposition in Chapel”
  ● Presented by Thomas Rolinger at CHIUW 2018

2.) Porting SPLATT to Chapel:

Mutex Pool

● SPLATT uses a mutex pool for some of the parallel MTTKRPO routines to synchronize access to matrix rows
● Chapel currently does not have a native lock/mutex module
  – Can recreate behavior with sync or atomic variables
  – We originally used sync variables, but later switched to atomic (see Performance Evaluation section).
Sync Var: Background

- Made a simpler benchmark to investigate
  - SPMD Stream triad that barriers
    
    ```
    coforall tid in 0..#numTasks {
      barrier.barrier();
      for i in chunk(1..m, numTasks, tid) do
        A[i] = B[i] + alpha * C[i];
    }
    ```

- Discovered that sync-based barrier serialized execution
Sync Var: Background and This Effort

**Background:** Qthread syncs optimized for producer/consumer
- Unblocked sync vars scheduled tasks onto the current thread
  - assumed producer would block, and consumer could reuse data in cache
- This is not ideal for sync vars used as locks/barriers
  - serialized all tasks onto the same thread

**This Effort:** Reschedule woken task onto the original thread
- Avoids task serialization, but can hurt producer/consumer perf
  - opened issue with Qthreads team, pursuing better options
  - in the meantime our workaround is better overall for Chapel
Sync Var: Impact

- Sync variables no longer serialize execution
  - Sync-based barrier on par with atomic-based barrier for STREAM

- SPLATT performance with sync var locks is much better

<table>
<thead>
<tr>
<th>Config</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17.1 Sync Locks</td>
<td>19.1s</td>
</tr>
<tr>
<td>1.18.0 Sync Locks</td>
<td>5.6s</td>
</tr>
<tr>
<td>Atomic Locks</td>
<td>5.4s</td>
</tr>
</tbody>
</table>
Sync Var: Negative Impact

- Caused a performance regression for threading
  - Unfairly benefitted from previous serialization
  - Not a code we are deeply invested in
Qthreads: Parallel I/O Improvements
Saw serious performance degradation with parallel I/O

- Especially when 2 Chapel executables ran concurrently on a node

```chapel
coforall t in 1..here.maxTaskPar {
    for i in 1..100 do
        writeln(t, " : ", i);
}
```

Starting first instance of `time -p ./io-slowdown`
0.12s
0.09s
0.30s
0.07s
Starting second concurrent instance of `time -p ./io-slowdown`
7.97s
7.97s
13.68s
13.68s

Output from 1st instance
Output from 2nd instance
Parallel I/O: This Effort and Impact

This Effort: Transitioned from spinlock to sync var lock
- Enabled by sync var serialization fixes

Impact: Improved parallel I/O performance
- Especially for concurrent runs

Starting first instance of `time -p ./io-slowdown`
- 0.07s (~0.12s previously)
- 0.07s
- 0.06s
- 0.03s
Starting second concurrent instance of `time -p ./io-slowdown`
- 0.27s (~10.0s previously)
- 0.28s
- 0.18s
- 0.18s
- 0.35s
Parallel I/O: Negative Impact

● Serial I/O performance suffered
  ● For uncontested access, an atomic lock is faster than a sync lock
  ● believe parallel I/O improvements outweigh these regressions
  ● advanced users can manually disable locking for serial I/O

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**Time to tree paircount**

- Array-of-Struct
- Struct-of-Array

**c vs chpl writing single newlines to stdout**

- chpl stdout
- C/chpl string global
- C/chpl c_string global
- chpl non-blocking
- C puts
- C printf
- C/chpl c_string local
- C/chpl string literal
Parallel I/O: Next Steps

- **Transition to a hybrid lock**
  - Use an atomic for uncontested access, fall back to sync if contested

- **Investigate compiler optimizations**
  - May be able to eliminate locking when access is provably serial
Qthreads: Other Sync Var Improvements
Sync Improvements: Background and Effort

**Background:** Qthreads has 2 sync variable implementations
- aligned_t – Full/Empty Bit state stored externally, 64 bits available
  - chapel sync vars map to this type (since we need to store 64-bit types)
- syncvar_t – 3 bits to store Full/Empty Bit state, leaving 61 bits for data
  - was used in runtime shim in a few places

**This Effort:** Change runtime shim uses of syncvar_t to aligned_t
- syncvar_t still has serialization issue (only fixed for aligned_t)
- aligned_t version is better tested (since Chapel types map to it)
Sync Improvements: Impact

- Performance improvements for several benchmarks
Bale Case Study
Bale: Background

- Bale is a collection of mini-applications in UPC/SHMEM
  - Tests various communication idioms and patterns
    - Histogram (stresses network atomics)
    - Indexgather (stresses remote GETs)
    - Toposort

- Bale also contains aggregated communication libraries
  - Compares elegant/intuitive code vs. more complex aggregated code
  - For our initial study, we focused on performance of elegant versions
    - implemented versions of histogram, indexgather, and toposort
    - started tuning performance of histogram first
Bale Histogram Background
Histogram: Background

- Histogram randomly updates an array of network atomics
- Idiom is similar to our atomic-based version of RandomAccess (RA)

```cpp
Default UPC
for(i = 0; i < T; i++) {
    counts[index[i]] += 1;
}
```

```chapel
Default Chapel
forall r in rindex { A[r].add(1); }
```

```cpp
Optimized UPC
for(i = 0; i < T; i++) {
    #pragma pgas defer_sync
    counts[index[i]] += 1;
}
lgp_barrier();
```
By default, network operations are “blocking”

- Have to wait for an acknowledgement (ACK) from remote locales
- Required by Memory Consistency Model (MCM)
  - “sequential consistency for data-race-free programs”

```plaintext
var a: atomic int;
on Locales[1] {
  a.add(1);
  writeln(a.read()); // must print 1
}
```

Blocking operations limit network injection rate

- Have to wait for round-trip network ACK
  - instead of issuing multiple operations back-to-back
Cray UPC/SHMEM can drop to more relaxed MCM modes

- “Use the ‘pgas defer_sync’ directive to force all references in the next statement to be non-blocking”

```c
Default UPC
for(i = 0; i < T; i++) {
    counts[index[i]] += 1;
}

Optimized UPC
for(i = 0; i < T; i++) {
    #pragma pgas defer_sync
    counts[index[i]] += 1;
} lgp_barrier();
```
● Chapel performance was ~15% behind default
  ● And ~5.5x off from the optimized variant
Faster Blocking Atomics
Faster Atomics: Background

- **Used to yield continuously while waiting for remote ACK**
  - Yielding allows for comm/compute overlap
  - Discovered that task-yield is more expensive than expected
    - Tasks often in middle of yield when ACK comes in

```c
cdi = post_fma(locale, post_desc)   // initiate transaction (post to NIC)

do {
    chpl_task_yield();             // yield every iter
    consume_all_outstanding_cq_events(cdi);
} while (!atomic_load_bool(&post_done));   // blocking wait for transaction to complete
```
Faster Atomics: This Effort

- **Switch to yielding initially, then every 64 tries**
  - Still allows for comm/compute overlap when numTasks > numCores
    - when not oversubscribed, can process ACK sooner
  - Value chosen experimentally, 32 and 128 also worked well
    - chose middle ground, longer-term solution is to optimize task-yields

```c
    cdi = post_fma(locale, post_desc)     // initiate transaction (post to NIC)

do {
  if ((iters & 0x3F) == 0) chpl_task_yield();  // yield initially, then 1/64 iters
  iters++;
  consume_all_outstanding_cq_events(cdi);
} while (!atomic_load_bool(&post_done));      // blocking wait for transaction to complete
```
Faster Atomics: Impact

- Improved blocking atomic performance
- Better performance for many-to-one atomic microbenchmark

![Remote AMO Performance Graph](image)
Faster Atomics: Impact

- Improved blocking atomic performance
- Better performance for RA-atomics benchmark
Faster Atomics: Histogram Impact

- Chapel performance on par with default UPC
  - Still ~4.5x off from the optimized variant
Buffered Atomics
Buffered Atomics: Background and Effort

**Background:** Chapel had no way to drop to more relaxed MCM
  - Foundation/placelholder in the spec: “Unordered Memory Operations”
  - but no implementation, source of optimized performance gap

**This Effort:** Added “buffered” atomics to express unordered ops
  - Operations are not sequentially consistent, must be explicitly flushed
  - Implemented in a package module:
    - [https://chapel-lang.org/docs/1.18/modules/packages/BufferedAtomics.html](https://chapel-lang.org/docs/1.18/modules/packages/BufferedAtomics.html)
  - Allowed for fast prototype without language/spec changes

```chapel
var a: atomic int;
a.addBuff(1);
writeln(a);          // can print 0 or 1
flushAtomicBuff();
writeln(a);          // must print 1
```
Buffered Atomics: This Effort

● Wrote a buffered version of histogram:

```
Default Chapel
forall r in rindex {  
  A[r].add(1);  
}

Optimized Chapel
forall r in rindex {  
  A[r].addBuff(1);  
}
flushAtomicBuff();
```

● Under the hood: operations stored in thread-local buffers
  ● Buffers are flushed when full or on calls to ‘flushAtomicBuff()’
  ● We initiate transactions all at once with:
    ● ugni “chained” transactions for CLE 5.2UP04 and up (up to 5x perf gain)
    ● non-blocking transactions for older versions of CLE (up to 2.5x perf gain)
Buffered Atomics: Impact

- Better performance for codes that can use buffered ops
  - ~1.5x improvement for many-to-one microbenchmark
Buffered Atomics: Impact

- Better performance for codes that can use buffered ops
  - ~4.5x improvement for buffered RA-atomics benchmark

![Graph showing RA Performance (GUPS) with different locales and cores]

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Buffered Atomics: Histogram Impact

- Chapel performance on par with default UPC
  - And for the optimized variant

![Bale Histo UPC vs Chapel](graph.png)
Bale Histogram Summary
In 1.17.1 blocking performance was ~15% behind UPC
- Optimized performance was ~5.5x off
■ In 1.18.0 performance is on par with UPC
  ■ Result of optimizing blocking atomics and adding buffered atomics

Bar Chart: Bale Histo UPC vs Chapel 1.18.0

- X-axis: Default vs Optimized
- Y-axis: MB/s per Node
- Green: UPC
- Blue: Chapel 1.18.0
Histogram: Next Steps

● Improve elegance of optimized histogram code
  ● `addBuff()` reveals too much about the implementation
    ● explicit flush is cumbersome
      ```
      forall r in rindex do
        A[r].addBuff(1);
        flushAtomicBuff();
      ```
  
  ● Add a more general syntax for super-relaxed operations
    ● Current implementation only supports atomic operations
      ```
      deferSync do forall r in rindex do // `deferSync’ as a proposed syntax
        A[r].add(1);
      ```

● Add compiler optimization to automatically perform transformation
  ● Not always possible, but cases like this should be straightforward
Bale: Summary and Next Steps

**Summary:** Ported Bale mini-apps to Chapel
- Optimized histogram to match UPC performance

**Next Steps:**
- Optimize `indexgather` and `toposort`
  - `indexgather` tuning is already underway
- Improve elegance
  - need a cleaner way to express unordered operations
- Start investigating buffered/aggregated examples
  - aggregation buffers updates to remote locales, permits bulk communication
Memory Leak Improvements
Memory Leaks: Background + This Effort

Background:
- Historically, Chapel testing has leaked a large amount of memory
- Chapel 1.15 and 1.16 closed major sources of large-scale leaks
- Chapel 1.17 reduced leaked memory in testing by another 50%

This Effort:
- Closed several classes of leaks reported by nightly testing:
  - leaks caused by using constructors rather than initializers
  - minor leaks in several library modules:
    - RegExp, DateTime, CPtr, List, FileSystem
  - leaks in tests that were fixed when converting to managed class types
- Just after cutting the 1.18 branch, closed a leak in CS sparse domains
  - (reflected in these notes, but not included in the release)
Memory Leaks for Examples in Release
Memory Leaks for Examples in Release

- Converted domain maps to use initializers
- Closed leak in test by converting to managed classes
- Reduced size of leaked record
-Switched from compiler-generated constructors to initializers
- Added new test involving sparse domains
- Closed sparse domain leak
Memory Leaks for All Tests

- Considering all tests, a similar story but noisier
  - Spikes typically due to new tests with user-level leaks being added
Memory Leaks: Remaining Leaks (as of 1.17)
Memory Leaks: Remaining Leaks (as of 1.18)
Memory Leaks: Remaining Leaks (as of Sept 19)

- Only 264 / 9137 tests still leaking
- ~1/3 of memory leaked by three tests using distributed sparse block arrays
- ~3/4 of leaking tests leak < 256 bytes
- ~45% of leaking tests leak < 64 bytes
Memory Leaks: Status

Status:

- From 1.17–1.18, leaks reduced by 25% in testing (w/ ~750 new tests)
  - leaks reduced by 60% compared to 1.17 with sparse domain fix
- Primary known cases of remaining leaks:
  - certain distributed sparse block cases
  - compiler-generated iterator classes in certain cases
  - aspects of global arrays of arrays
  - certain domain map meta-data
  - certain first-class-functions
  - user-level leaks in tests themselves
Memory Leaks: Next Steps

Next Steps:

- Continue working through remaining leaks as a background task
- Once no leaks remain, make addition of new leaks a failure mode

![Graph showing size of remaining leaks by test number with April 2018 and Sept 2018 memory leaks highlighted]
For More Information

For additional optimization and benchmark changes in the 1.18 release, refer to the ‘Performance Optimizations’, ‘Cray-specific Performance Optimizations’, ‘Memory Improvements’, and ‘Example Codes’ sections in the CHANGES.md file.
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