Minimizing MPI Resource Contention in Multithreaded Multicore Environments

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Overview

MPI Background
  MPI Objects
  MPI & Threads

Naïve Reference Counting
  Basic Approach
  An Improvement

Hybrid Garbage Collection
  Algorithm
  Analysis

Results
  Benchmark and Platform
  The Numbers
Most MPI objects are **opaque objects**

- Created, manipulated, and destroyed via **handles** and functions

- Object handle examples: MPI_Request, MPI_Datatype, MPI_Comm

- MPI types such as MPI_Status are *not* opaque (direct access to status.MPI_ERROR is valid)

- In this talk, **object** always means an opaque object
The *Premature Release* Problem

**Example**

```c
MPI_Datatype tv;

MPI_Type_vector(..., &tv);
MPI_Type_commit(&tv);

MPI_Type_free(&tv);
```

This is a premature release. `comm` and `tv` are still in use at user-release time.
The *Premature Release* Problem

Example

```c
MPI_Datatype tv;
MPI_Comm comm;

MPI_Comm_dup(MPI_COMM_WORLD, &comm);
MPI_Type_vector(..., &tv);
MPI_Type_commit(&tv);

MPI_Comm_free(&comm);
MPI_Type_free(&tv);
```

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The *Premature Release* Problem

**Example**

```c
MPI_Datatype tv;
MPI_Comm comm;
MPI_Request req;
MPI_Comm_dup(MPI_COMM_WORLD, &comm);
MPI_Type_vector(..., &tv);
MPI_Type_commit(&tv);
MPI_Irecv(buf, 1, tv, 0, 1, comm, req);
MPI_Comm_free(&comm);
MPI_Type_free(&tv);
... arbitrarily long computation ...
MPI_Wait(&req);
```

This is a premature release. comm and tv are still in use at user-release time
Supporting the “simple” case is trivial:
- \texttt{MPI\_Type\_vector} \leftrightarrow \texttt{malloc}
- \texttt{MPI\_Type\_free} \leftrightarrow \texttt{free}

The more complicated premature release case requires more effort, typically reference counting.
Terminology Note

- To minimize confusion, let us refer to functions like `MPI_Type_free` as **user-release functions** and their invocation as **user-releases**.
- `ref` means “reference”
MPI Reference Counting Semantics

- MPI objects must stay alive as long as logical references to them exist. Usually corresponds to a pointer under the hood.
- Objects are born with only the user’s ref.
- The user can release that ref with a user-release (e.g. MPI_Comm_free)
- MPI operations logically using an object may acquire a reference to that object, which is then released when finished.
- An MPI object is no longer in use and eligible for destruction when there are no more references to the object.
MPICH2 Objects

- All MPICH2 objects are allocated by a custom allocator (not directly by malloc/free).
- All objects have a common set of header fields.
- We place an atomically-accessible, reference count ("refcount") integer field here.
- This field is initialized to 1 on object allocation.
The Naïve Algorithm

\(A, B, \text{ and } C\) are opaque MPI objects

1. If \(A\) adds a ref to \(B\), atomically increment \(B\)’s reference count.

2. If ownership of a ref to \(B\) changes hands from \(A\) to \(C\), don’t change \(B\)’s reference count.

3. If \(A\) releases a ref to \(B\), atomically decrement and test \(B\)’s reference count against zero. If zero, deallocate the object.
Reference Counting Example

Example

<table>
<thead>
<tr>
<th>refcount</th>
<th>tv</th>
<th>comm</th>
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</tbody>
</table>

- MPI_Datatype `tv`;  
- MPI_Comm `comm`;  
- MPI_Request `req`;  
- MPI_Comm_dup(MPI_COMM_WORLD, &comm);  
- MPI_Type_vector(..., &tv);  
- MPI_Type_commit(&tv);  
- MPI_Irecv(buf, 1, tv, 0, 1, comm, req);  
- MPI_Comm_free(&comm);  
- MPI_Type_free(&tv);  
- ... arbitrarily long computation ...  
- MPI_Wait(&req);
Downsides

Example

```c
MPI_Request req[NUM_RECV];
for (i = 0; i < NUM_RECV; ++i)
    MPI_Irecv(..., &req[i]); // ATOMIC{++(c->ref_cnt)}
MPI_Waitall(req); // for NUM_RECV: ATOMIC{--(c->ref_cnt)}
```

- Different threads running on different cores/processors will fight over the cache line containing the ref count for the communicator and datatype.
- Even the waitall will result in NUM_RECV atomic decrements for each shared objects.
An Improvement

- Many codes (and benchmarks) don’t use user-derived objects.
- Predefined objects (MPI_COMM_WORLD, MPI_INT, etc) are not explicitly created in the usual fashion.
- Their lifetimes are bounded by MPI_Init and MPI_Finalize and cannot be freed.
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**Upshot:** simply don’t maintain reference counts for predefined objects.
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■ Predefined objects (MPI_COMM_WORLD, MPI_INT, etc) are not explicitly created in the usual fashion.
■ Their lifetimes are bounded by MPI_Init and MPI_Finalize and cannot be freed.
■ *Upshot:* simply don’t maintain reference counts for predefined objects.
■ Easy to implement in MPICH2; completely removes contention in the critical path.
■ Doesn’t help us at all for user-derived...
Problem: MPI_Comm and MPI_Datatype refcount contention (possibly others too, MPI_Win)

- Communicators/datatypes/etc are usually long(ish) lived.
- MPI_Requests are frequently created and destroyed.
- Suggests a garbage collection approach to manage communicators, etc.
**Definitions**

**GCMO**  Garbage Collection Managed Object. These are long-lived, contended objects: communicators, datatypes, etc.

**Transient**  Short-lived, rarely contended objects: requests

- \( G_\ell \)  The set of live GCMOs, must not be deallocated
- \( G_e \)  The set of GCMOs eligible for deallocation
- \( T \)  The set of transient objects
High Level Approach

- Disable reference counting on GCMO objects due to transient objects. Other refcounts remain!
- Add a live/not-live boolean in the header of all GCMOs.
- Maintain $T$, $G_\ell$, and $G_e$ somehow (we used lists).
- At creation, GCMOs are added to $G_\ell$. Refcount starts at 2 (user ref and garbage collector ref).
- When a GCMO’s refcount drops to 1, move it to $G_e$.
- Periodically run a garbage collection cycle (next slide).
Garbage Collection Cycle

1. lock the allocator if not already locked
2. *Reset*: Mark every $g \in G_e$ not-live.
3. *Mark*: For each $t \in T$, mark any referenced GCMOs (eligible or not) as live.
4. *Sweep*: For each $g \in G_e$, deallocate if $g$ is still marked not-live.
5. unlock the allocator if we locked it in step 1
### Garbage Collection Example

**refcount**

<table>
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<tr>
<th>tv</th>
<th>comm</th>
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</table>

... arbitrarily long computation ...
Analysis

- When $|G_e| > 0$, collection cycle cost bound, fixed # GCMO refs per transient object: $O(|G_e| + |T|)$
- When $|G_e| > 0$, cycle cost bound, variable # GCMO refs per transient object: $O(|G_e| + r_{avg}|T|)$
- $|G_\ell|$ is not present in bound $\implies$ GC performance penalty only for “prematurely” freed GCMOs and outstanding requests.
When to Collect?

- MPI_Finalize, obviously
- Collection at new GCMO allocation time makes sense.
- Flexible here: could be probabilistic, could be a function of memory pressure, could be a timer.
- GCMO creation is not usually expected to be lightning fast, won’t be in most inner loops.
- We already hold the allocator’s lock.
- GCMO user-release time is an option, but makes less sense.
Benchmark

- **MPI_THREAD_MULTIPLE** benchmarks and applications are rare/nonexistent.
- We wrote a benchmark based on the Sequoia Message Rate Benchmark (SQMR).
- Each iteration posts 12 nonblocking sends and 12 nonblocking receives, then calls MPI_Waitall.
- 10 warm-up iterations, then time 10,000 iterations, report average time per message.
- All are 0-byte messages.
Test Platform

- ALCF’s Surveyor Blue Gene/P system.
- 4 – 850 MHz PowerPC cores
- 6 bidirectional network links per node, arranged in a 3-D torus
- multicore, but unimpressively so
- network-level parallelism is the key here, a serialized network makes this work pointless
Message Rate Results — Absolute

- **strategy / object-type**
  - naive / built-in
  - no-predef / built-in
  - GC / built-in
  - no-predef / derived
  - GC / derived

Message Rate (millions per second)

<table>
<thead>
<tr>
<th>Message Rate (millions per second)</th>
<th># threads</th>
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<tbody>
<tr>
<td>0.4</td>
<td>1</td>
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<tr>
<td>0.6</td>
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<td>0.8</td>
<td>3</td>
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<td>1.0</td>
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Summary

- MPI specifies clear semantics for opaque object lifetimes that map trivially to reference counting.
- Reference counting with multithreading is usually expensive due to cache line contention.
- Suppressing refcounts for predefined objects (MPI_COMM_WORLD) is cheap and safe. Doesn’t help user-defined objects.
- Hybrid refcount+GC can pull the performance bottleneck out of the critical path.
- Hybrid scheme is fairly easy to retrofit into an existing refcount mechanism.
Questions?
(backup slides)
Memory Consistency Implementation Issues

- PPC has a relaxed memory consistency model
- bad case (relaxed Store-Store ordering):

**Example**

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
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<tbody>
<tr>
<td>1 req-&gt;comm=C</td>
<td>MPI_Comm_create(C)</td>
</tr>
<tr>
<td>2</td>
<td>// run GC cycle, free C</td>
</tr>
<tr>
<td>3 MPI_Comm_free(C)</td>
<td>// (--ref)==0, now eligible</td>
</tr>
<tr>
<td>4 // (--)ref)==0, now eligible</td>
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<td>6</td>
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<td>7</td>
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<tr>
<td>8 // use freed req-&gt;comm</td>
<td></td>
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- memory barrier seems unnecessary on x86/x86_64 (only Store-Load order violated, plus atomics are full barriers)
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<tr>
<td>1 req-&gt;comm=C</td>
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<tr>
<td>2 mem_barrier(lwsync)</td>
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<tr>
<td>3 MPI_Comm_free(C)</td>
</tr>
<tr>
<td>4 // (--ref)==0, now eligible</td>
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<tr>
<td>8 // use freed req-&gt;comm SAFE</td>
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