Minimizing MPI Resource Contention in Multithreaded Multicore Environments

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Overview

MPI Objects

- 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

```
MPI_Datatype tv;




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


MPI_Type_free(&tv);
```

The *Premature Release* Problem

Example

```
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);
```

The *Premature Release* Problem

Example

```
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

User Convenience, Implementer Pain

- Supporting the “simple” case is trivial:
  - `MPI_Type_vector` ↦ `malloc`
  - `MPI_Type_free` ↦ `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, 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

refcount tv	comm	
-	-	`MPI_Datatype tv;`
-	-	`MPI_Comm comm;`
-	-	`MPI_Request req;`
-	1	`MPI_Comm_dup(MPI_COMM_WORLD, &comm);`
1	1	`MPI_Type_vector(..., &tv);`
1	1	`MPI_Type_commit(&tv);`
2	2	`MPI_Irecv(buf, 1, tv, 0, 1, comm, req);`
2	1	`MPI_Comm_free(&comm);`
1	1	`MPI_Type_free(&tv);`
1	1	`... arbitrarily long computation ...`
0	0	`MPI_Wait(&req);`

Downsides

Example

```
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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- 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…

One Man's Trash…

- 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_ℓ	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_ℓ, and G_e somehow (we used lists)
- At creation, GCMOs are added to G_ℓ. 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		
tv	comm	
-	-	`MPI_Datatype tv;`
-	-	`MPI_Comm comm;`
-	-	`MPI_Request req;`
-	2	`MPI_Comm_dup(MPI_COMM_WORLD, &comm);`
2	2	`MPI_Type_vector(..., &tv);`
2	2	`MPI_Type_commit(&tv);`
2	2	`MPI_Irecv(buf, 1, tv, 0, 1, comm, req);`
2	1	`MPI_Comm_free(&comm);`
1	1	`MPI_Type_free(&tv);`
1	1	`... arbitrarily long computation ...`
1	1	`MPI_Wait(&req);`
0	0	`// something triggers GC cycle`

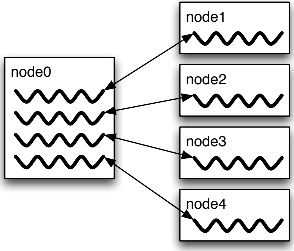
Analysis

- When $|G_e| > 0$, collection cycle cost bound, fixed # GCMO refs per transient object: $\mathcal{O}(|G_e| + |T|)$
- When $|G_e| > 0$, cycle cost bound, variable # GCMO refs per transient object: $\mathcal{O}(|G_e| + r_{\text{avg}}|T|)$
- $|G_\ell|$ 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

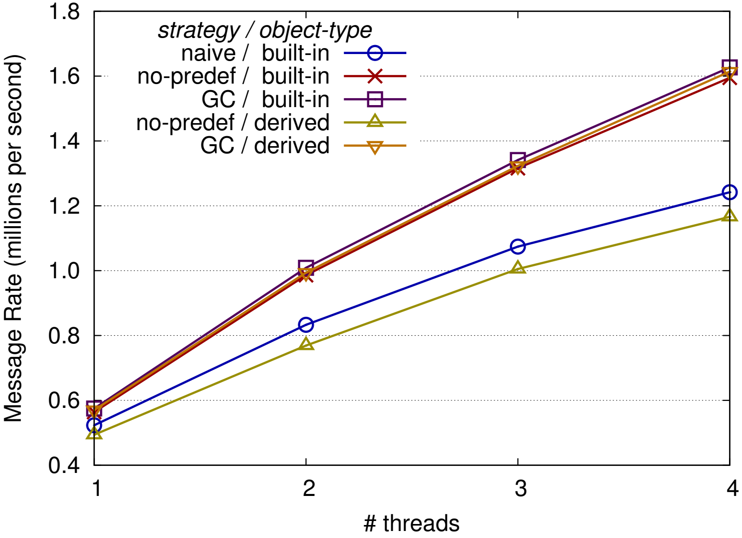


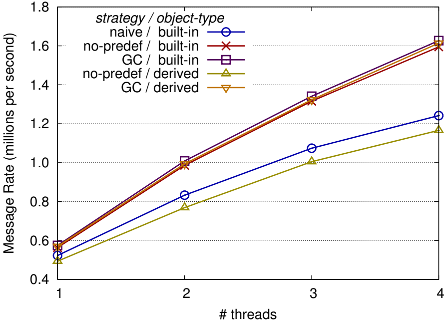
- `MPI_THREAD_MULTIPLE` benchmarks and applications are rare/nonexistent.
- We wrote a benchmark based on the Sequoia Message Rate Benchmark (SQMR).
- Each iteration posts 12 nonblocking sends and 12 nonblocking receives, then calls `MPI_Waitall`.
- 10 warm-up iterations, then time 10,000 iterations,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

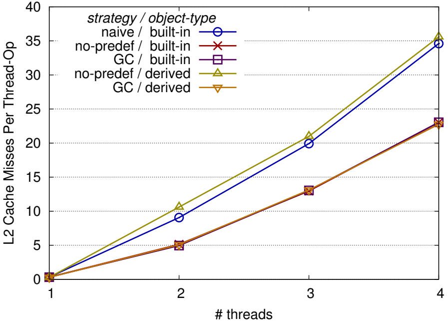
Test Platform

- 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)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
1
2
3
4
threads


strategy / object-type
naive / built-in
no-predef / built-in
GC / built-in
no-predef / derived
GC / derived
L2 Cache Misses Per Thread-Op
40
35
30
25
20
15
10
5
0
1
2
3
4
threads

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?

Questions?

(backup slides)

Memory Consistency Implementation Issues

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

Example

	Thread 0	Thread 1
1	`req->comm=C`	
2		
3	`MPI_Comm_free(C)`	
4	`// (--ref)==0, now eligible`	
5		`MPI_Comm_create(C)`
6		`// run GC cycle, free C`
7		
8	`// use freed req->comm`	

- memory barrier seems unnecessary on x86/x86_64 (only Store-Load order violated, plus atomics are full barriers)

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8	`// use freed req->comm` BAD!	

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Example

	Thread 0	Thread 1
1	`req->comm=C`	
2	~~`mem_barrier(lwsync)`~~	
3	`MPI_Comm_free(C)`	
4	`// (--ref)==0, now eligible`	
5		`MPI_Comm_create(C)`
6		`// run GC cycle, free C`
7		
8	`// use freed req->comm` SAFE	

- memory barrier seems unnecessary on x86/x86_64 (only Store-Load order violated, plus atomics are full barriers)