Recent Progress on Adaptive MPI

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Charm++ Workshop 2020

Overview

- Introduction to AMPI
- Recent Work
  - Collective Communication Optimizations (Sam)
  - Automatic Global Variable Privatization (Evan)

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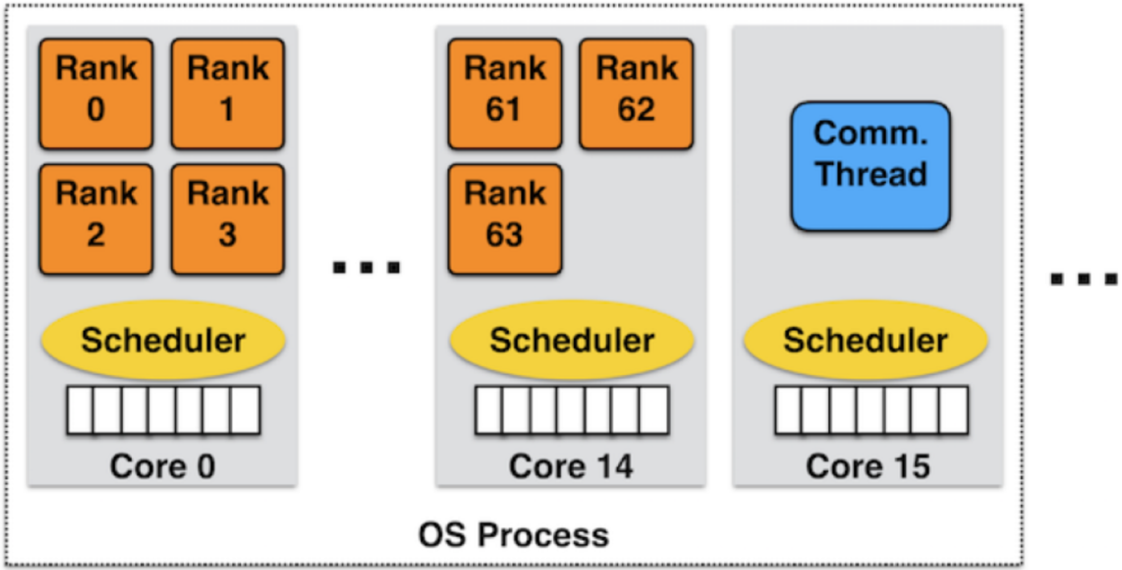
Introduction

Motivation

- Variability in various forms (SW and HW) is a challenge for applications moving toward exascale
    - Task-based programming models address these issues
- How to adopt task-based programming models?
    - Develop new codes from scratch
    - Rewrite existing codes, libraries, or modules (and interoperate)
    - Implement other programming APIs on top of tasking runtimes

Background

- AMPI virtualizes the ranks of MPI_COMM_WORLD
  - AMPI ranks are user-level threads (ULTs), not OS processes



Background

- AMPI virtualizes the ranks of MPI_COMM_WORLD
  - AMPI ranks are user-level threads (ULTs), not OS processes
  - Cost: virtual ranks in each process share global/static variables
  - Benefits:
    - Overdecomposition: run with more ranks than cores
    - Asynchrony: overlap one rank's communication with another rank's computation
    - Migratability: ULTs are migratable at runtime across address spaces

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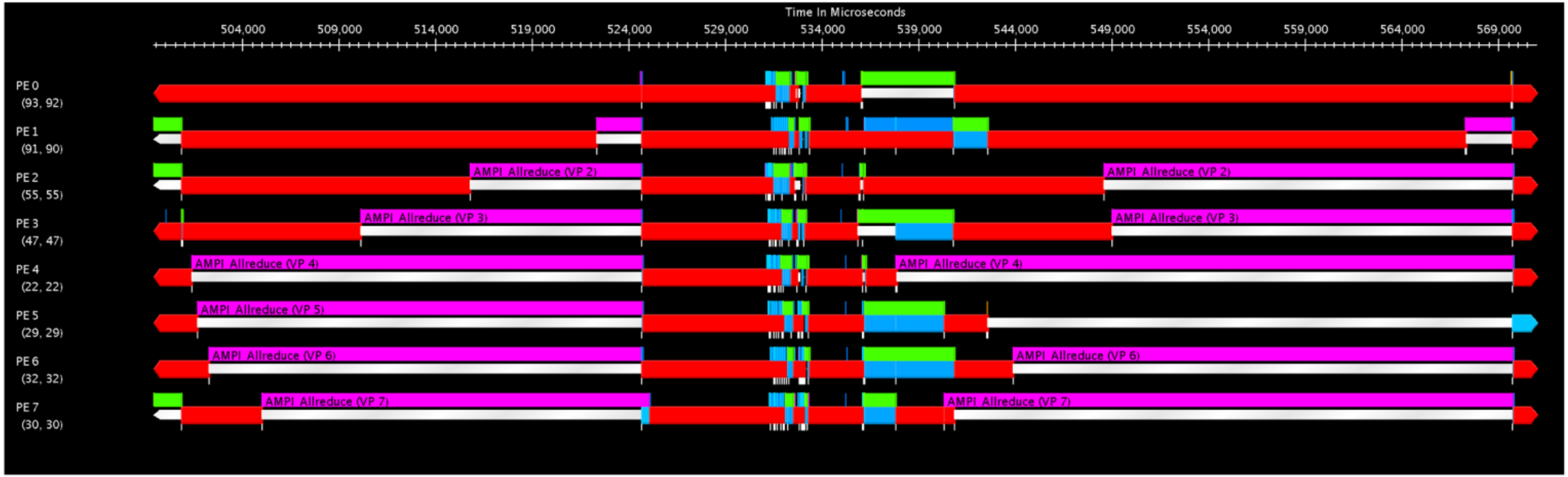
AMPI Benefits

- Communication Optimizations
  - Overlap of computation and communication
  - Communication locality of virtual ranks in shared address space
- Dynamic Load Balancing
  - Balance achieved by migrating AMPI virtual ranks
  - Many different strategies built-in, customizable
  - Isomalloc memory allocator serializes all of a rank's state
- Fault Tolerance
  - Automatic checkpoint-restart within the same job

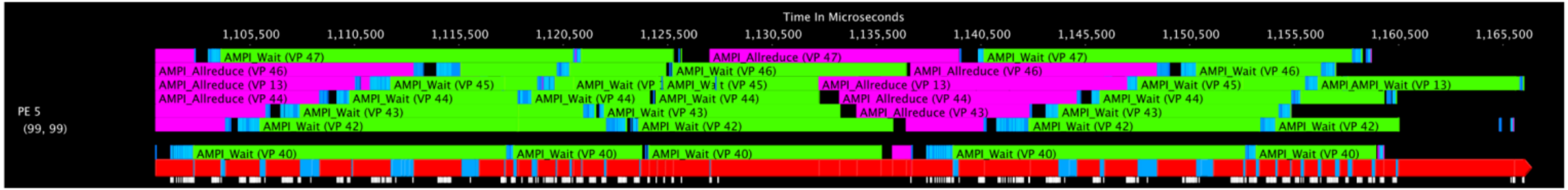
AMPI Benefits: LULESH-v2.0

Computation	
MPI_Isend	
MPI_Wait(all)	
MPI_Allreduce	
Idle	

No overdecomposition or load balancing (8 VPs on 8 PEs):

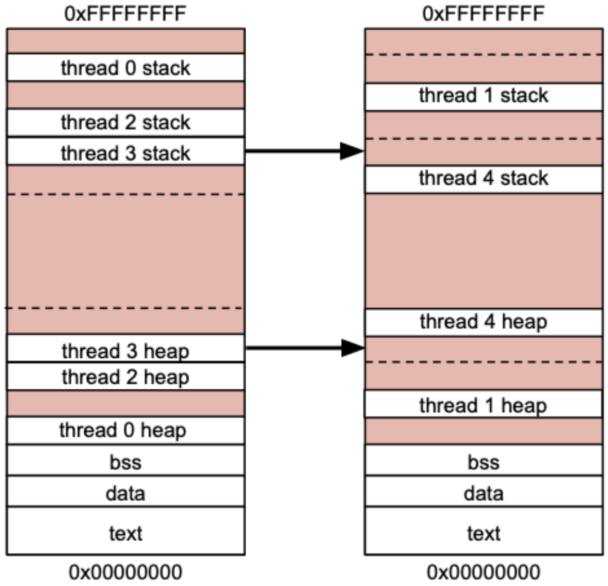


With 8x overdecomposition, after load balancing (7 VPs on 1 PE shown):



Migratability

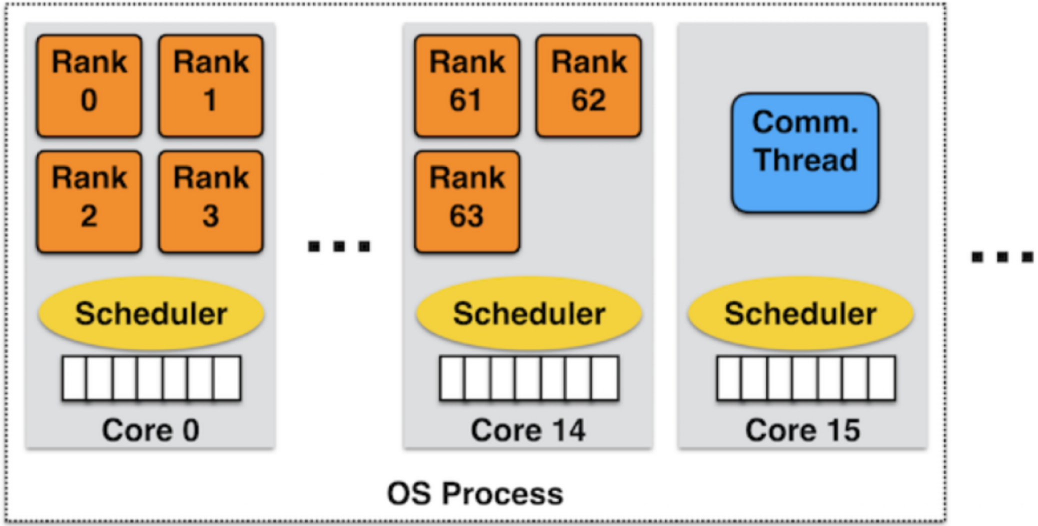
- Isomalloc memory allocator *reserves* a globally unique slice of virtual memory space in each process for each virtual rank
- Benefit: no user-specific serialization code
  - Handles the user-level thread stack and all user heap allocations
  - Works everywhere except BGQ and Windows
  - Enables dynamic load balancing and fault tolerance



Communication Optimizations

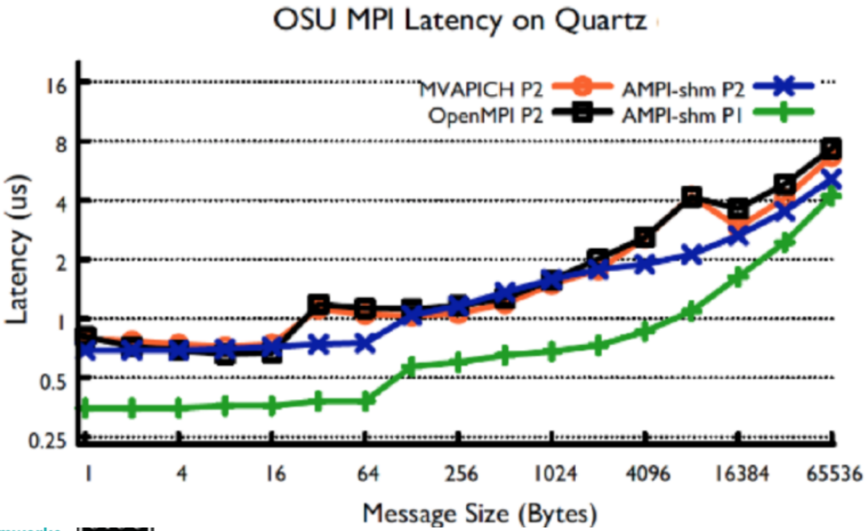
Communication Optimizations

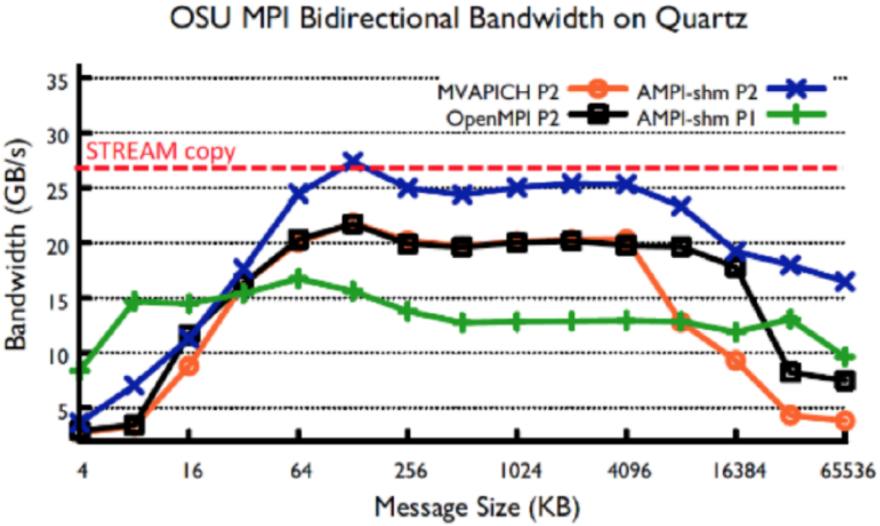
- AMPI exposes opportunities to optimize for communication locality:
  - Multiple ranks on the same PE
  - Many ranks in the same OS process



Point-to-Point Communication

- Past work: optimize for point-to-point messaging within a process
  - No need for kernel-assisted interprocess copy mechanism
  - Motivated generic Charm++ Zero Copy APIs





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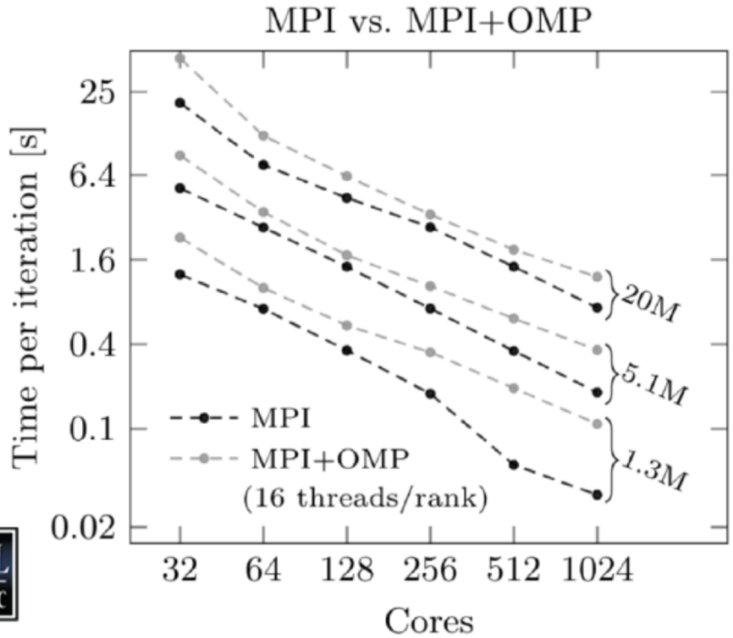
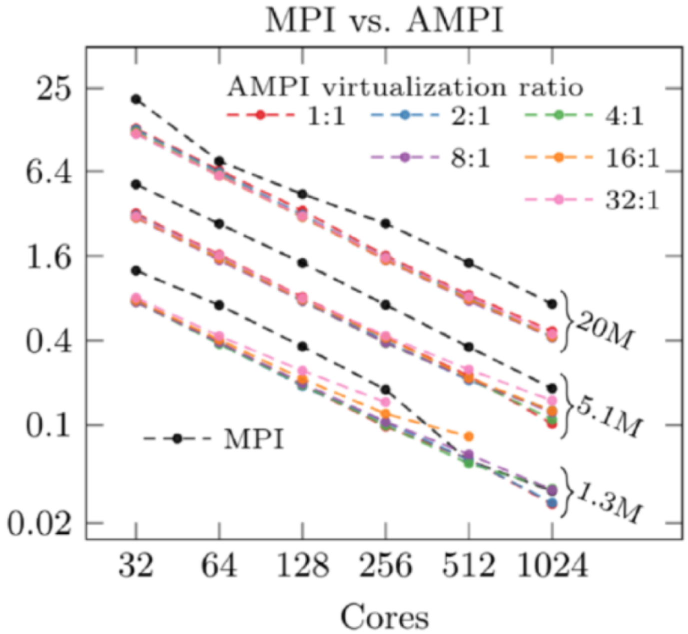
Point-to-Point Communication

- Application study: XPACC's *PlasCom2* code
  - AMPI outperforms MPI (+ OpenMP), even without LB





Collective Communication

- Virtualization-aware collective implementations avoid *O(VP)* message creation and copies
  - [nokeep] optimized to avoid msg copies on recv-side of bcasts
  - Zero Copy APIs to match MPI’s buffer ownership semantics
  - For reductions, avoid CkReductionMsg creation & copy
  - Revamping Sections/CkMulticast for subcommunicator collectives

Collective Communication

- Node-aware reductions: small msg optimizations
  - Sender-side streaming: no intermediate CkReductionMsg creation & copy
  - Dedicated shared buffer per node per comm

Version	CrayMPI VP=1 (usec)	AMPI VP=1 (usec)	AMPI VP=16 (usec)
Original	**1.24**	5.32	9.81
Sender-side streaming	---	5.35	5.71
… + dedicated shared buffer	---	**1.77**	**3.18**

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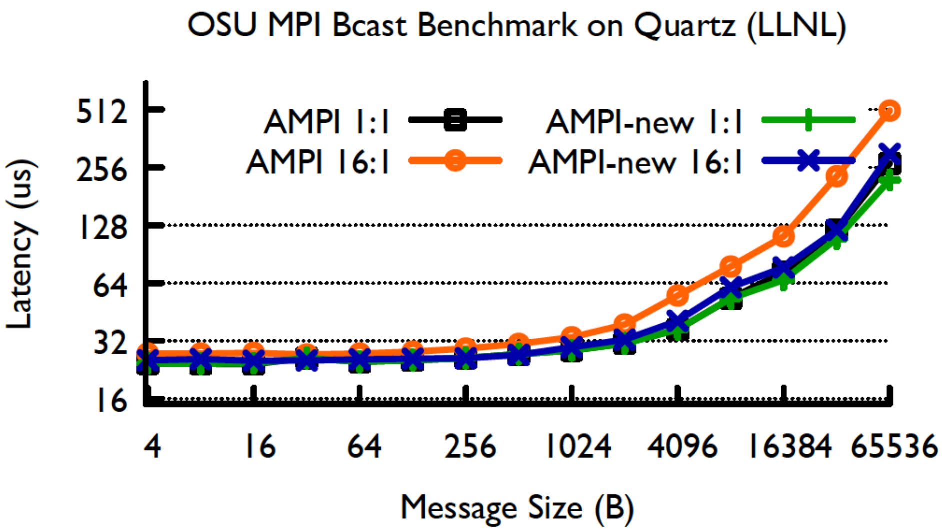
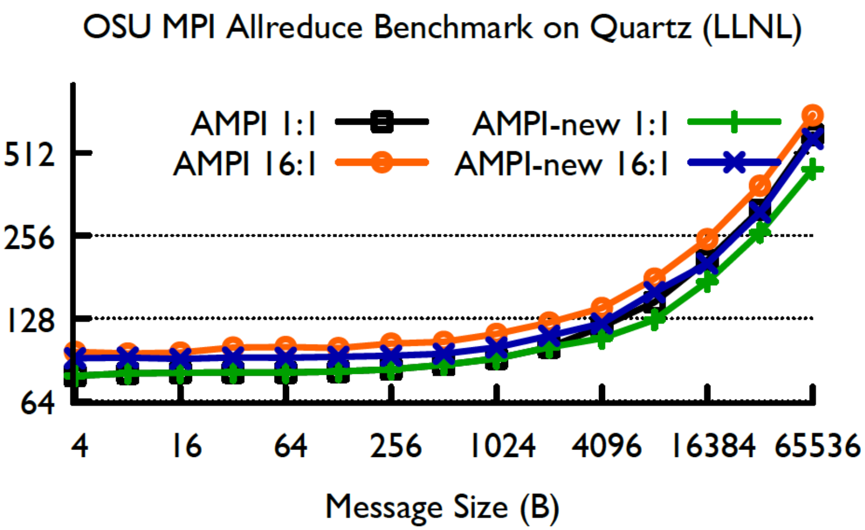
Collective Communication

- Node aware reductions: large msg optimizations





Memory Usage

- Recent study of memory usage by AMPI applications
  - User-space zero copy communication b/w ranks in shared address space -> lower rendezvous threshold
    - Avoid overheads of kernel-assisted IPC
  - Led to hoisting AMPI's read-only memory storage to node-level
    - Predefined datatype objects, reduction ops, groups, etc.
  - Developed in-place rank migration support via RDMA
    - Zero copy PUP API for large buffer migration (Isomalloc)

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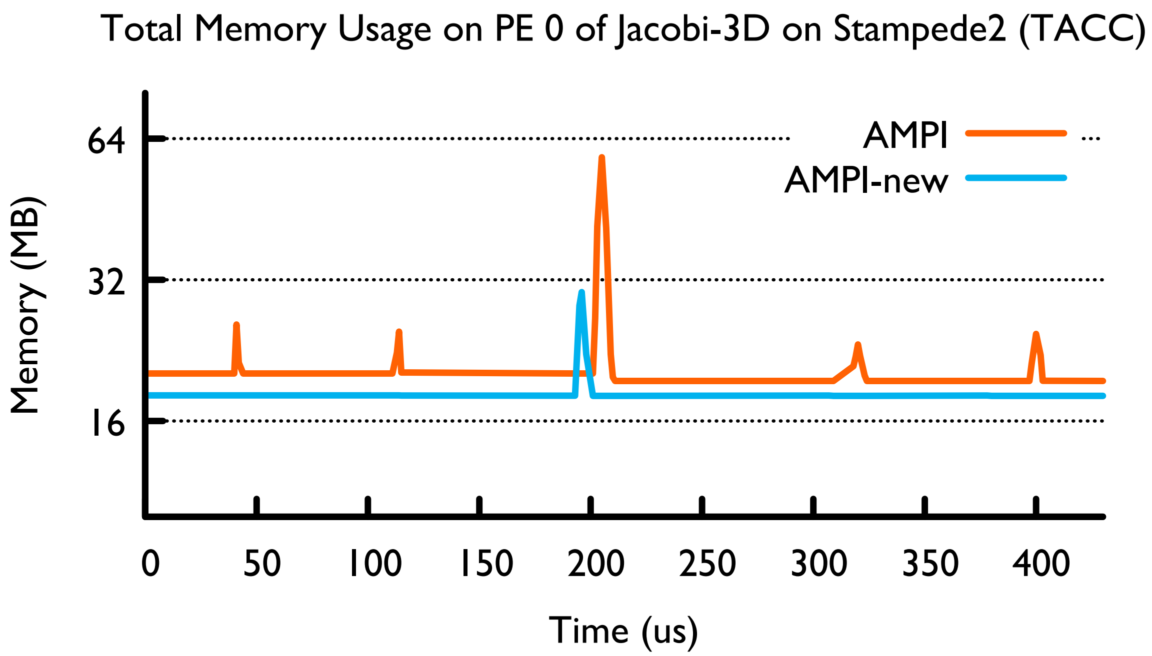
Memory Usage



Automatic Privatization

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Privatization Problem

Illustration of unsafe global/static variable accesses:

```
int rank_global;

void print_ranks(void)
{
  MPI_Comm_rank(MPI_COMM_WORLD, &rank_global);

  MPI_Barrier(MPI_COMM_WORLD);

  printf("rank: %d\n", rank_global);
}
```

Privatization Solutions

- Manual refactoring
  - Developer encapsulates mutable global state into struct
  - Allocate struct on stack or heap, pass pointer as part of control flow
  - Most portable strategy
  - **Can require extensive developer effort and invasive changes**

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Privatization Method Goals

- Ease of use: Method should be as automated as possible
- Portability
  - Portable across OSes, compilers
  - Require few/no changes to OS, compiler, or system libraries
- Feature support
  - Handle both *extern* and *static* global variables
  - Support for static and shared linking
  - Support for runtime migration of virtual ranks (using Isomalloc)
- Optimizable: Can share read-only state across virtual ranks in node

Privatization Methods

- First-generation automated methods
  - Swapglobals: GOT (global offset table) swapping
    - No changes to code: AMPI runtime walks ELF table, updating pointers for each variable
    - Does not handle *static* variables
    - Requires obsolete *GNU ld* linker version (< 2.24 w/o patch, < ~2.29 w/ patch)
    - O(n) context switching cost
    - Deprecated
  - TLSglobals: Thread-local storage segment pointer swapping
    - Add *thread_local* tag to global variable declarations and definitions (but not accesses)
    - Supported with migration on Linux (GCC, Clang 10+), macOS (Apple Clang, GCC)
    - O(1) context switching cost
    - Good balance of ease of use, portability, and performance

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Privatization Solutions

- Source-to-source transformation tools
  - Camfort, Photran, ROSE tools explored in the past
  - Clang/Libtooling-based tools are promising
    - Prototype C/C++ TLSglobals transformer created at Charmworks
    - Interested in building encapsulation transformer (more complex)
    - Flang/F18 merged into LLVM 11, hope to see Fortran Libtooling support
  - Some bespoke scripting efforts

Privatization Methods

- Second-generation automated methods
  - PiPglobals: Process-in-Process Runtime Linking (thanks RIKEN R-CCS)
  - FSglobals: Filesystem-Based Runtime Linking
- How they work
  - *ampicc* builds the MPI program as a PIE shared object (process-independent executable)
  - PIE binaries store and access globals relative to instruction pointer
  - AMPI runtime uses dynamic loader to instantiate a copy for each rank
    - PiPglobals: Call glibc extension *dlmopen* with unique *Lmid_t* namespace index per-rank
    - FSglobals: Make copies of .so on disk for each rank, call *dlopen* on them normally
- Integrated into Charm's nightly unit testing on production machines

Privatization Methods

- PiPglobals and FSglobals have drawbacks
  - PiPglobals requires patched PiP-glibc for >11 virtual ranks per process
  - FSglobals slams the filesystem making copies
  - FSglobals does not support programs with their own shared objects
  - Neither supports migration: Cannot Isomalloc code/data segments
- How to resolve drawbacks?
  - Patch ld-linux.so to intercept mmap allocations of segments?
  - Get hands dirty at runtime... **new method: PIEglobals**

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Privatization Methods: PIEglobals

- PIEglobals: Position-Independent Executable Runtime Relocation
  - Leverage existing .so loading infrastructure from PiP/FSglobals
  - AMPI processes the shared object at program start
    - *dlopen*: dynamically load shared object once per node
    - *dl_iterate_phdr*: get list of program segments in memory
    - duplicate code & data segments for each virtualized rank w/ Isomalloc
    - scan for and update PIC (position-independent code) relocations in data segments and global constructor heap allocations to point to new privatized addresses
    - calculate privatized location of entry point for each rank and call it
  - Global variables become **privatized** and **migratable**

Privatization Methods: PIEglobals

- Pitfalls
  - Program startup overhead (ex. miniGhost: ~2 seconds)
  - Debugging is difficult: debug symbols don’t apply to copied segments
    - Debug without PIEglobals (no virtualization) as much as possible
    - Helpful GDB commands: *call pieglobalsfind($rip)* or *call pieglobalsfind((void *)0x...)*
  - Relocation scanning can incur false positives
    - Solution in development: Open two copies using *dlmopen*, scan contents pairwise
  - Machine code duplication causes icache bloat and migration overhead
    - Solutions: *posix_memfd* mirroring within nodes; extend Isomalloc bookkeeping
  - Requires Linux and glibc v2.2.4 or newer (v2.3.4 for *dlmopen*)
- Successes: miniGhost, Nekbone
- Frontiers: OpenFOAM, mpi4py

Conclusion

- AMPI is increasingly valuable for a growing set of applications
  - Benefits apparent even in applications without load imbalance
  - Close to running complex legacy codes with virtualization easily
- Recent work spans the full stack of AMPI
  - Conformance to the MPI standard and conventions of other MPIs
  - Communication and memory improvements
  - More automation for privatization of legacy code
  - Working closely with more application developers
- Rebranding as **Charm MPI** to emphasize underlying technology

Questions?

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Privatization Methods

- Proposed Methods
  - MPC (Multi-Processor Computing) `-fmpc-privatize`: requires compiler and linker support

AMPI + PiP: Implementation Details

1. Compile MPI user binary as PIE (Position Independent Executable)
2. For each rank, call *dlmopen* with a unique namespace index (`lmid`)
   - `void *dlmopen (Lmid_t lmid, const char *filename, int flags);`
3. Use *dlsym* to look up and call each namespaced handle's entry point
4. Global variables will be privatized with no modification to user program code
   - PIE binaries locate .data immediately following .text in memory
   - PIE global variables are accessed relative to the instruction pointer
   - *dlmopen* creates a separate copy of the binary in memory for each namespace

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AMPI + PiP Details

Implementation Hurdles:

- Cannot simply compile AMPI programs as PIE and call *dlmopen*
  - Depending on approach, would either
    - Privatize entire Charm++/AMPI runtime system
      - Runtime would not function
      - Waste of memory
    - Prevent *dlmopen*'ed binary from seeing launcher's AMPI symbols
  - Instead, restructure headers and link with a function pointer shim
  - Only user program needs to be PIE

ampi_functions.h:

```
AMPI_FUNC(int, MPI_Send, const void *msg, int count,
          MPI_Datatype type, int dest, int tag, MPI_Comm comm)
```

mpi.h:

```
#ifdef AMPI_USE_FUNCPTR
  #define AMPI_FUNC(return_type, function_name, ...) \
    extern return_type (* function_name)(__VA_ARGS__);
#else
  #define AMPI_FUNC(return_type, function_name, ...) \
    extern return_type function_name(__VA_ARGS__);
#endif
#include "ampi_functions.h"
```

ampi_funcptr.h:

```
struct AMPI_FuncPtr_Transport {
  #define AMPI_FUNC(return_type, function_name, ...) \
    return_type (* function_name)(__VA_ARGS__);
  #include "ampi_functions.h"
};
```

ampi_funcptr_loader.C (linked with AMPI runtime):

```
void AMPI_FuncPtr_Pack(struct AMPI_FuncPtr_Transport * x) {
  #define AMPI_FUNC(return_type, function_name, ...) \
    x->function_name = function_name;
  #include "ampi_functions.h"
}
```

ampi_funcptr_shim.C (linked with MPI user program):

```
void AMPI_FuncPtr_Unpack(struct AMPI_FuncPtr_Transport * x) {
  #define AMPI_FUNC(return_type, function_name, ...) \
    function_name = x->function_name;
  #include "ampi_functions.h"
}
```