Checkpointing the Un-checkpointable: MANA and the Split-Process Approach

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Table of Contents

Outline

DMTCP History

The DMTCP project and antecedents began almost 15 years ago, and is widely used today:
`http://dmtcp.sourceforge.net/publications.html`

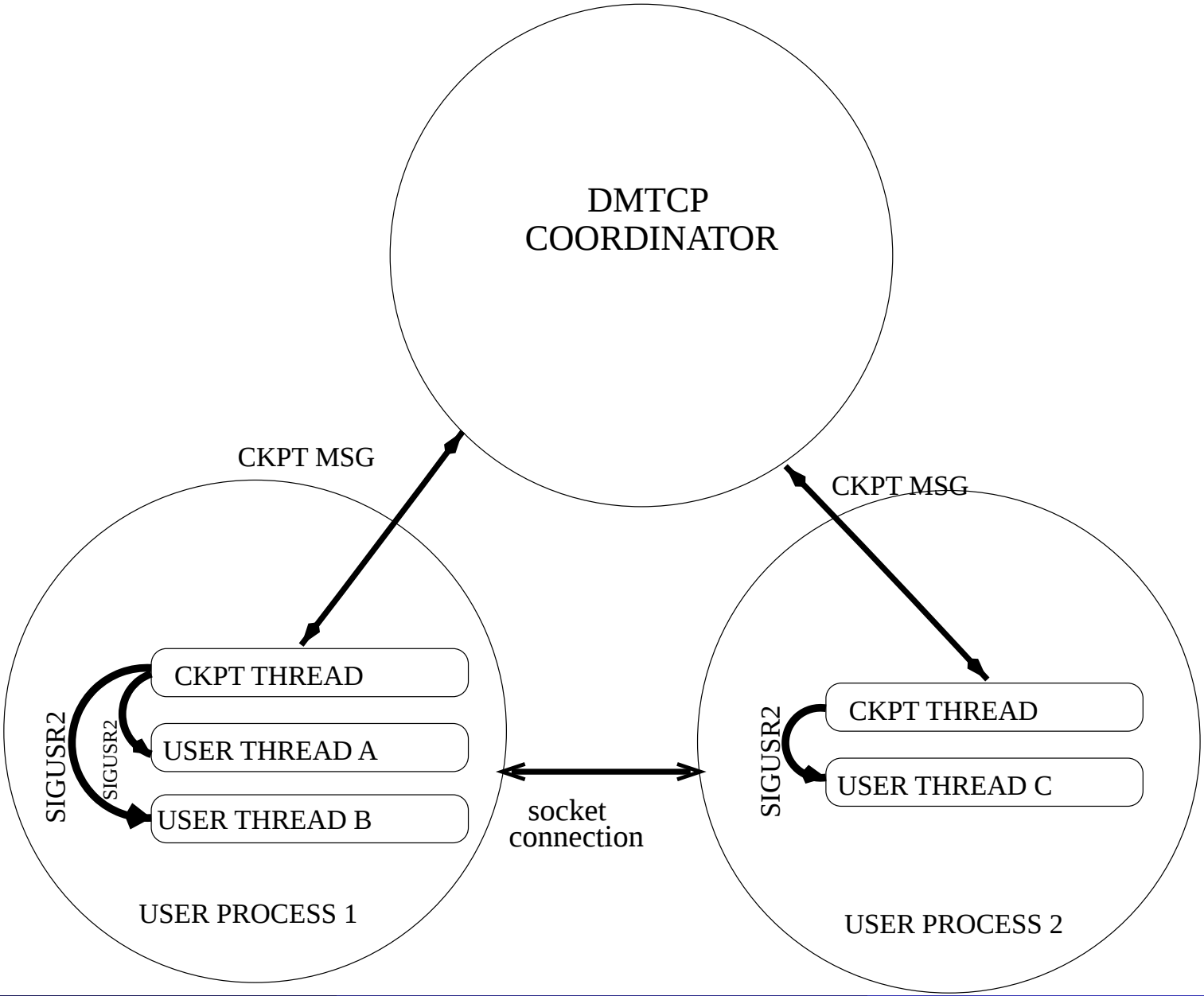
Typical use case for HPC: 12-hour batch time slot, an application is expected to finish in 18 hours.
(NOTE: A resource manager such as SLURM can send a signal one hour before the end of the time slot, giving the application time to checkpoint; DMTCP can then transparently checkpoint the state.)

Ease of use (unprivileged and transparent):

```
dmtcp_launch a.out arg1 arg2 ...
dmtcp_command --checkpoint # from other terminal or window
dmtcp_restart ckpt_a.out_*.dmtcp
```

(DMTCP also works for programs that are multi-threaded, distributed, MPI-based, ...)

DMTCP Architecture: Coordinated Checkpointing



Fundamental Research Question for the DMTCP Team

"What are the limits of checkpointing applications in the real-world?"

PROBLEM: An application may store a session id, tty, network peer address, TMPDIR for temporary files, process id, thread id, etc. On restart, some or all of these are likely to change.

SOLUTION: Process virtualization: interpose on all calls to such ids; replace actual id by DMTCP-defined virtual id.
PRINCIPLE: "Never let the application see a real id!"

Scalability:
Checkpointing HPCG: 32,752 CPU cores), and (NAMD: 16,368 CPU cores) for checkpointing MPI applications natively over InfiniBand at TACC:
"System-level Scalable Checkpoint-Restart for Petascale Computing", Jiajun Cao et al., *Int. Conf. on Parallel and Dist. Sys.* (ICPADS'16), 2016
*(To the best of our knowledge, this is **100 times larger** than the previously largest transparent checkpointing study in the literature.)*

Outline

DMTCP Plugins

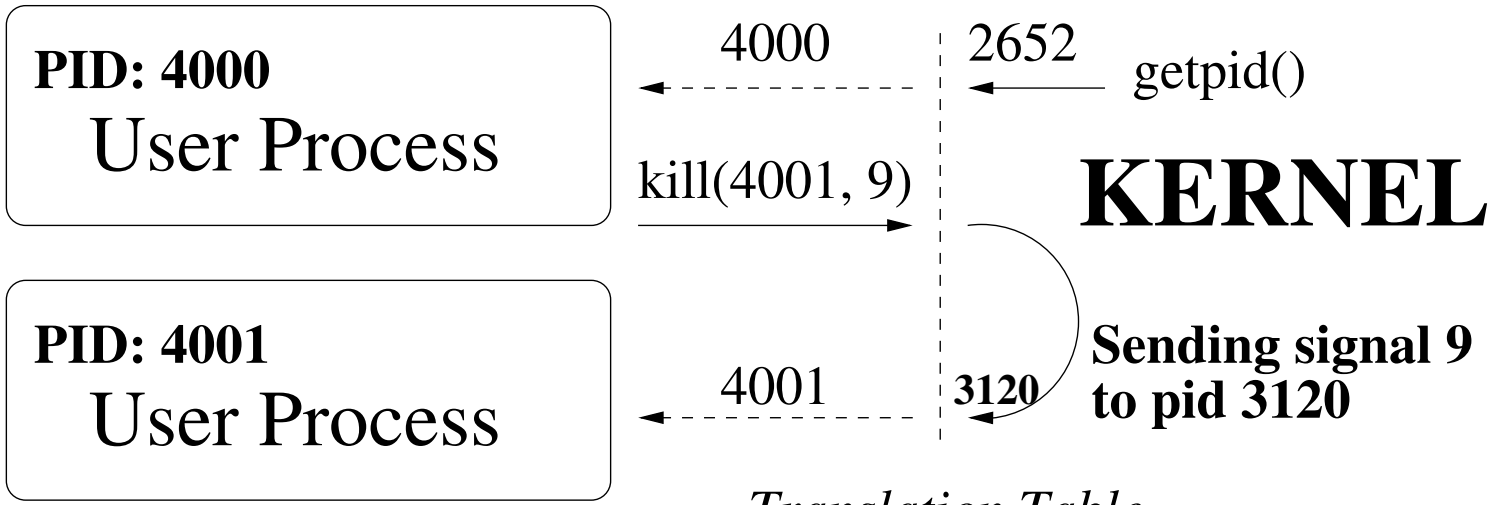
WHY PLUGINS?

- Processes must talk with the rest of the world!
- *Process virtualization:* virtualize the connections to the rest of the world

In short, a plugin is responsible for modeling an external subsystem, and then creating a semantically equivalent construct at the time of restart.

A Simple DMTCP Plugin: Virtualizing the Process Id

- **PRINCIPLE:**
  The user sees only virtual pids; The kernel sees only real pids



Translation Table

Virt. PID	Real PID
4000	2652
4001	3120

Plugins for EDA: A Real-world Example

EDA is "Electronic Design Automation" (circuit design for chips).
Part of a four-year collaboration between DMTCP team and Intel:

> "Be Kind, Rewind — Checkpoint & Restore Capability for Improving Reliability of Large-scale Semiconductor Design", I. Ljubuncic, R. Giri, A. Rozenfeld, and A. Goldis, IEEE HPEC-14, Sept., 2014.
> *(published solely by Intel co-authors)*

Fictional scenario with ball-park numbers (no particular vendor):

- Software circuit simulation: about 1 million times slowdown
- Hardware emulation at back-end: about 1 thousand times slowdown
- Cost of back-end hardware emulator: about $800,000
- **Use case A** (for a new CPU design): Boot Microsoft Windows overnight with emulator, and then test Microsoft Office.
- **Use case B**: Boot Microsoft Windows overnight with emulator, and checkpoint. In later iterations, restart, and then test Microsoft Office.

The above fictional scenario requires a DMTCP plugin to model the back-end emulator. *See publications with emulator vendors for details.*

Outline

Goal of Proxies

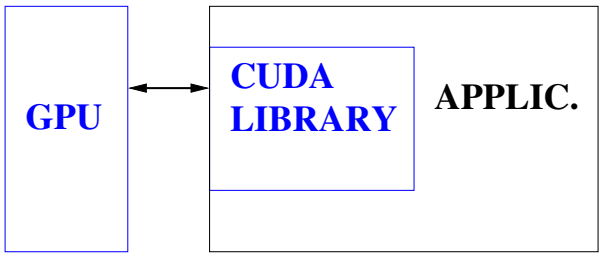
GOAL: ***To convince you of a general proxy paradigm for handling the "hard" checkpointing challenges that remain.***

We take as testbeds two such "hard" examples:

1. Checkpoint a CUDA application running on a GPU (Problem: how to save and restore the state of GPU hardware)
   (joint with Rohan Garg, Apoorve Mohan, Michael Sullivan)
   To appear, IEEE Cluster'18; see, also, technical report:
   `https://arxiv.org/abs/1808.00117`
2. Checkpoint MPI on NERSC/Cori supercomputer (with GNI network; no checkpoint-restart service to support it)
   (a long story: coming next in Part Two of this talk)

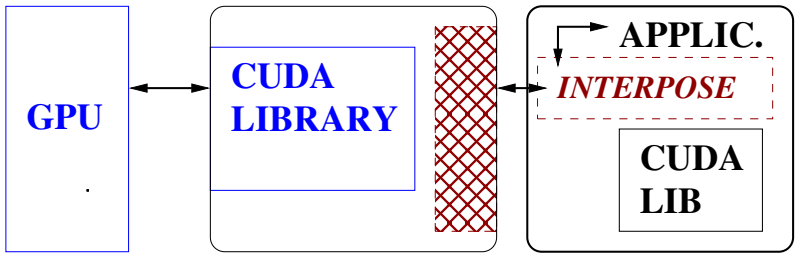
Proxies: The Secret Sauce

BEFORE:



Application

AFTER:



Application Process

Proxy Process

Basic Idea of a Proxy for System Services

PROBLEM: Often, system services are provided with the help of an auxiliary system that cannot be checkpointed.

EXAMPLES: GPU device hardware; MPI auxiliary process or MPI coordinator; sshd (ssh daemon); VNC server; etc.

SOLUTION:

A. Split user process into two: an application process with all of the application state; and a proxy process communicating with hardware or software for system services.

B. System service requests are passed from application process to proxy process through inter-process communication, and pass result back.

C. At checkpoint time, the proxy process is temporarily disconnected, and the application process is checkpointed as an isolated "vanilla" Linux process. (Note: the proxy process must be in a quiescent state (no unfinished system service tasks) at checkpoint time.)

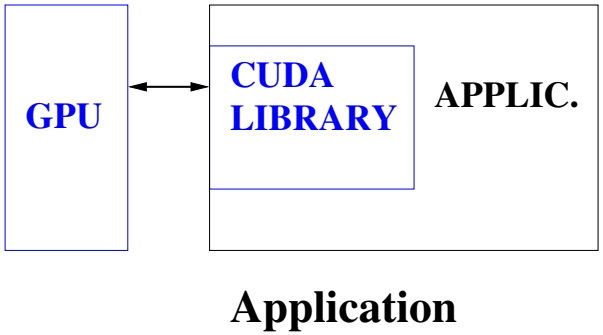
D. At restart time, a *new* proxy process re-connects with the system service and with the restarted application. The application process then replays some old system service requests, restoring system to a state that equivalent to pre-checkpoint time.

For more on this, see the thesis of Rohan Garg

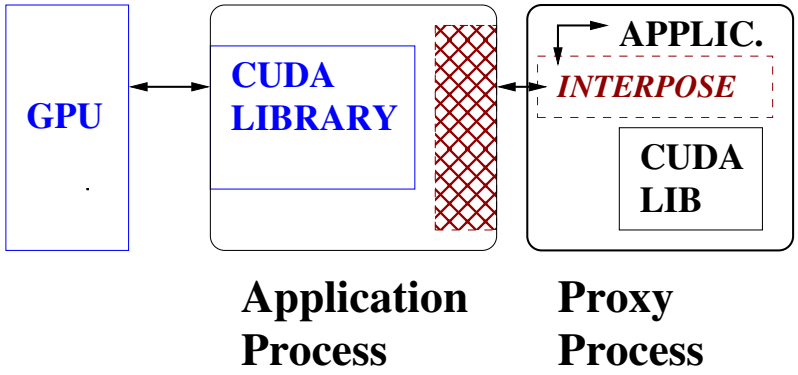
(NOTE: Proxies have been used before. For example, this is the basis of an old trick for checkpointing VNC sessions. We propose it here as a general paradigm for checkpoint-restart.)

Proxies: The Secret Sauce (again)

BEFORE:



AFTER:



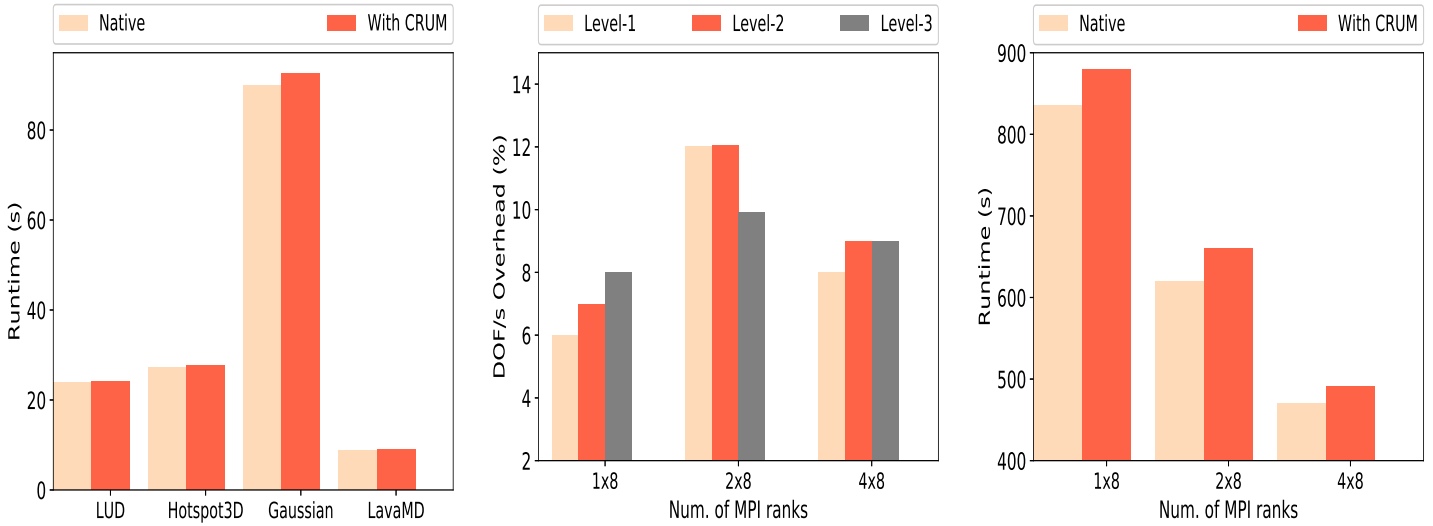
*First tell them what you're going to say; then say it;
and then tell them what you said.

CRUM: "Checkpoint-Restart for Unified Memory" for CUDA

Proxy-based shadow paging for CUDA UVM (Unified Virtual Memory)

- *Shadow UVM page synchronization:* Catches memory transfers between proxy and application through memory permissions and segfault detection. The difficulty for transparent checkpointing with CUDA-managed memory: **How to make this efficient?**
  See the CRUM paper (Algorithm 1, shadow-page synchronization) for details.
- Enables fast *forked checkpointing model* for UVM memory that overlaps writing a checkpoint image to stable storage, while the application continues. *Almost free benefit of our approach!* (This was difficult in the past due to the need to share memory among the GPU device, and the UVM-based host that was split among parent and forked child processes.)

CRUM (Checkpoint-Restart for CUDA Unified Memory): Runtime



a Rodinia Benchmark.

b HPGMG-FV Benchmark.

c HYPRE Benchmark.

Figure: Runtime overheads for different benchmarks under CRUM.

Operating environment: Four NVIDIA Tesla P100's per node; CUDA 8 (max config: four nodes with 4 GPUs per node and 8 MPI ranks per node)

Outline

MANA for MPI: MPI-Agnostic Network-Agnostic Transparent Checkpointing

Full paper with details at:

"MANA for MPI: *MPI-Agnostic Network-Agnostic* Transparent Checkpointing", by R. Garg, G. Price, and G. Cooperman, *High Performance Distributed Computing* (HPDC'19)

Not just an implementation, but a flexible principle with many applications:

- **IDEA:** Load two independent programs into a *single* process, sharing a single address space. (For a different approach, see "Process-in-process", HPDC'18 from RIKEN et al., employing multiple link maps/dlmopen.)
- **LOW OVERHEAD!** This completely eliminates the overhead of the proxy approach. (No need for shared memory, cross-memory-attach (cma), XPMEN. One program can directly pass an internal pointer to the other program.)
- **Isolate the MPI/network libraries into their own program; completely separate from the program running the MPI application.**

MANA for MPI: MPI-Agnostic Network-Agnostic Transparent Checkpointing (cont.)

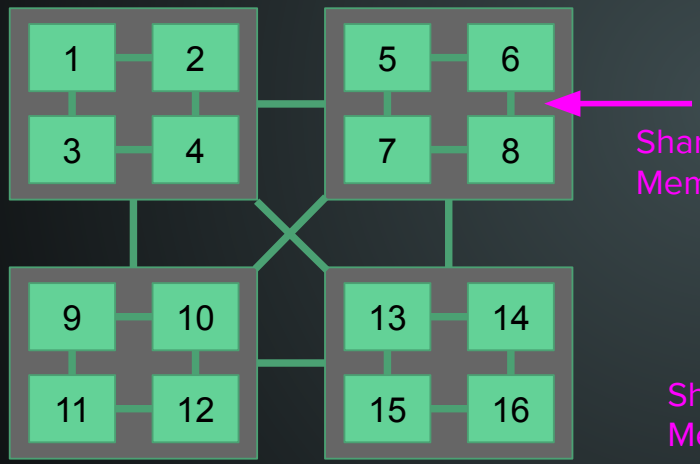
FEATURES OF THE SPLIT-PROCESS APPROACH:

- Can dynamically change configuration of underlying MPI at runtime.
  (Why not? The MPI libraries run in a separate program, unrelated to the MPI application program.)
- Can even change the choice of the underlying MPI and network (e.g., InfiniBand vs. Cray GNI) at runtime!
  (Why not? The MPI and network libraries run in a separate program, unrelated to the MPI application program.)
- Can even migrate to a new cluster at runtime, in which the number of CPU cores per nodes is different!
  (Why not? The binding of the MPI libraries to the CPU cores is part of a separate program, unrelated to the MPI application program.)

Puzzle

Can you solve checkpointing on...

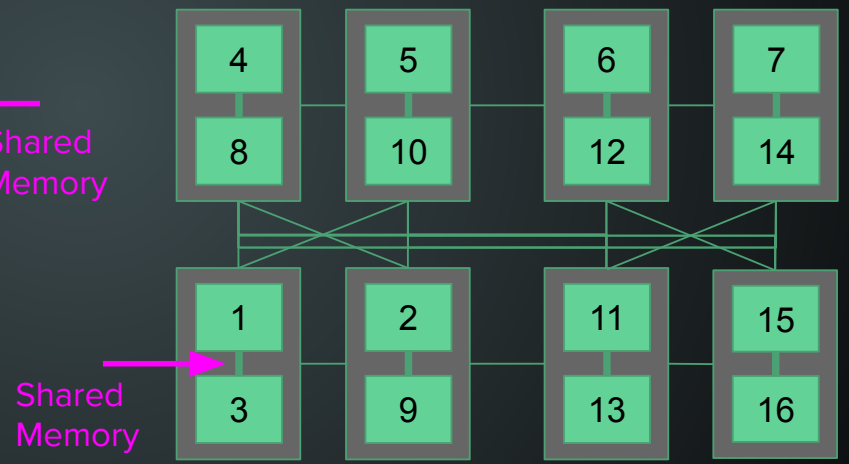
Cray MPI over Infiniband



4 Nodes, 4 Cores/Ranks per Node

And restart on...

MPICH over TCP/IP

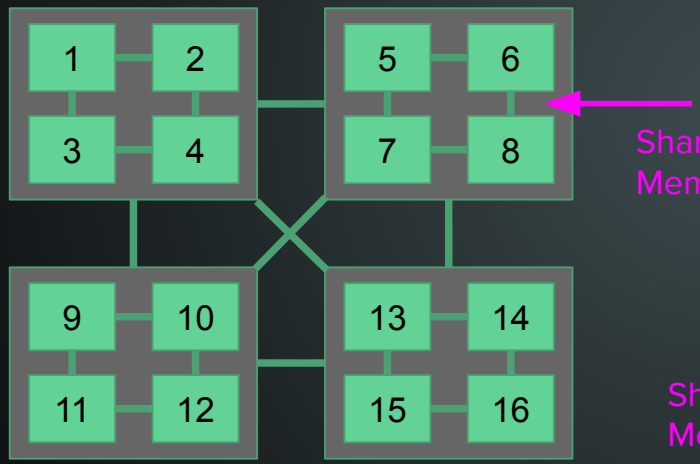


8 Nodes, 2 Cores/Ranks per Node

Cross-Cluster Migration

It is now possible to checkpoint on

Cray MPI over Infiniband



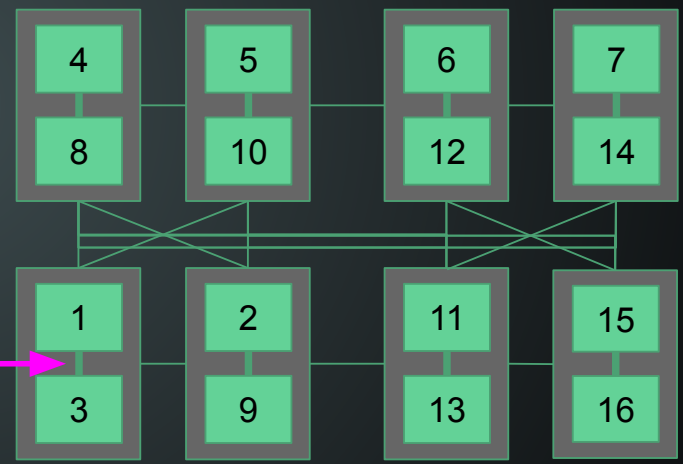
4 Nodes, 4 Cores/Ranks per Node

Shared Memory

Shared Memory

And restart on...

MPICH over TCP/IP



8 Nodes, 2 Cores/Ranks per Node

Transparency and Agnosticism

Transparency

1. No re-compilation and no re-linking of application
2. No re-compilation of MPI
3. No special transport stack or drivers

Agnosticism

1. Works with any libc or Linux kernel
2. Works with any MPI implementation (MPICH, CRAY MPI, etc)
3. Works with any network stack (Ethernet, Infiniband, Omni-Path, etc).

Alas, poor transparency, I knew him Horatio...

Transparent checkpointing could die a slow, painful death.

1. Open MPI Checkpoint-Restart service (Network Agnostic; cf. Hursey et al.)
   - MPI implementation provides checkpoint service to the application.
2. BLCR
   - Utilizes kernel module to checkpoint local MPI ranks
3. DMTCP (MPI Agnostic)
   - External program that wraps MPI for checkpointing.

These, and others, have run up against a wall:

MAINTENANCE

The M x N maintenance penalty

MPI:

- MPICH
- OPEN MPI
- LAM-MPI
- CRAY MPI
- HP MPI
- IBM MPI
- SGI MPI
- MPI-BIP
- POWER-MPI
- ....

Interconnect:

- Ethernet
- InfiniBand
- InfiniBand + Mellanox
- Cray GNI
- Intel Omni-path
- libfabric
- System V Shared Memory
- 115200 baud serial
- Carrier Pigeon
- ....

The M x N maintenance penalty

MPI:

- MPICH
- OPEN-MPI
- LAM-MPI
- CRAY MPI
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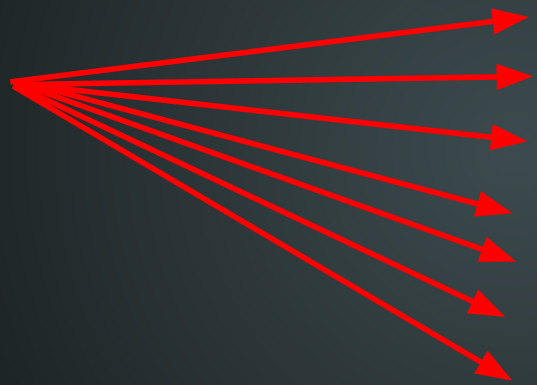
- MPI-BIP
- POWER-MPI
- ....

Network Agnostic



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The M x N maintenance penalty

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- MPICH
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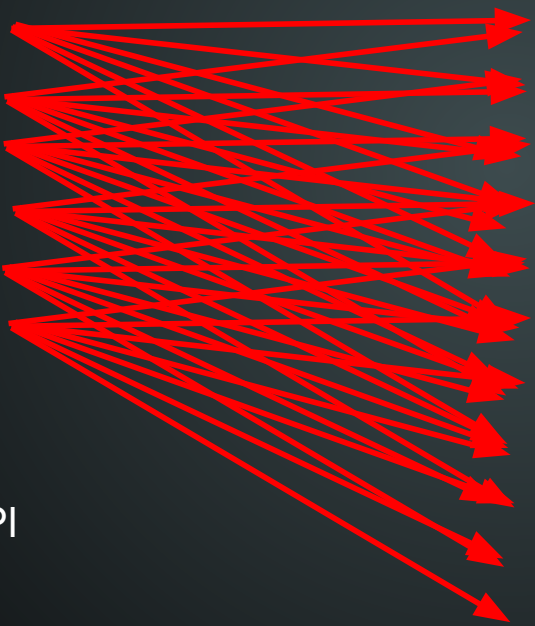
- ....

MPI and Network Agnostic



Interconnect:

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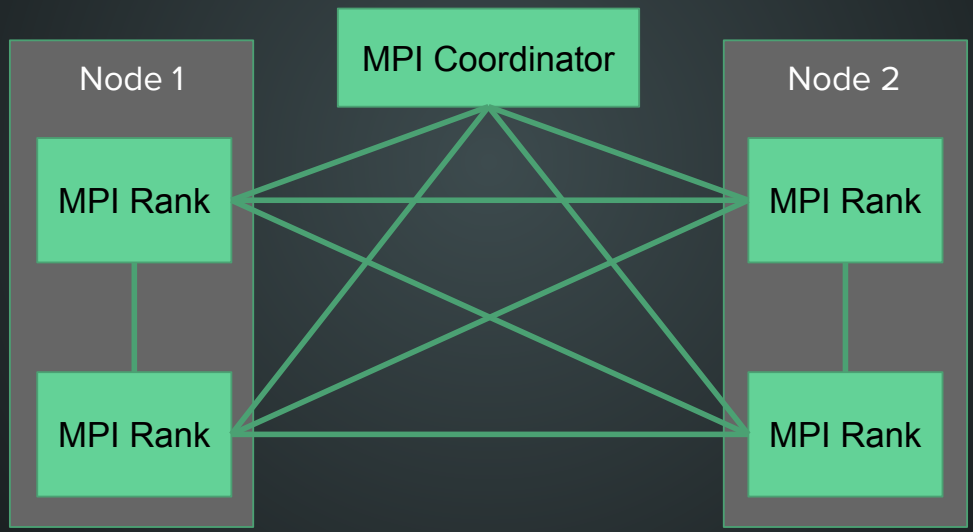
- Carrier Pigeon
- ....

MANA: MPI-Agnostic, Network-Agnostic

The problem stems from checkpointing both the MPI coordinator and the MPI lib.



MANA: MPI-Agnostic, Network-Agnostic

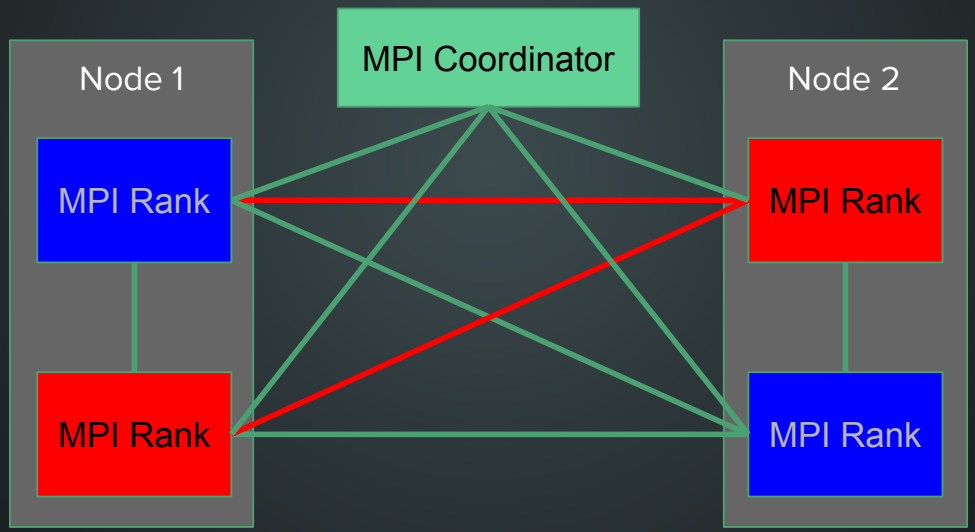
The problem stems from checkpointing MPI - both the coordinator and the library.

Connections

Groups

Communicators

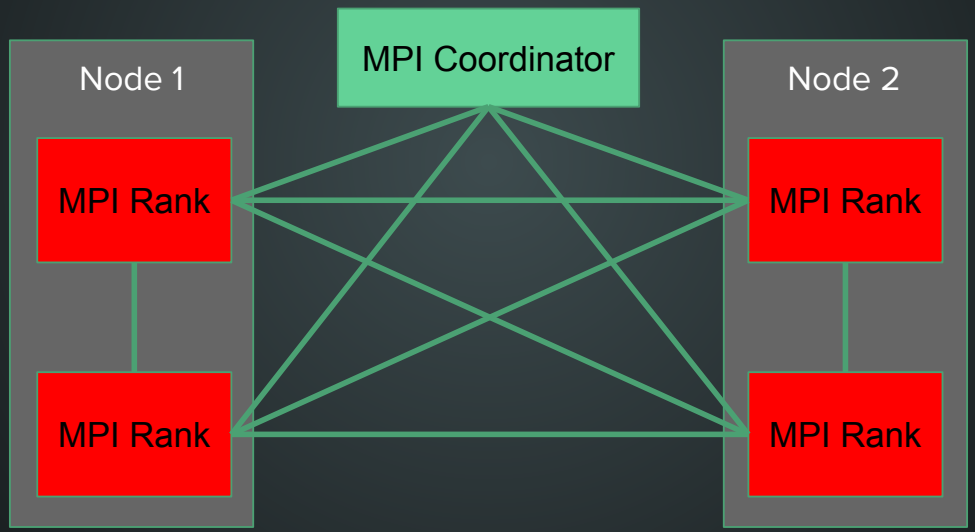
Link State



Achieving Agnosticism

Step 1: Drain the Network

Chandy-Lamport Algorithm

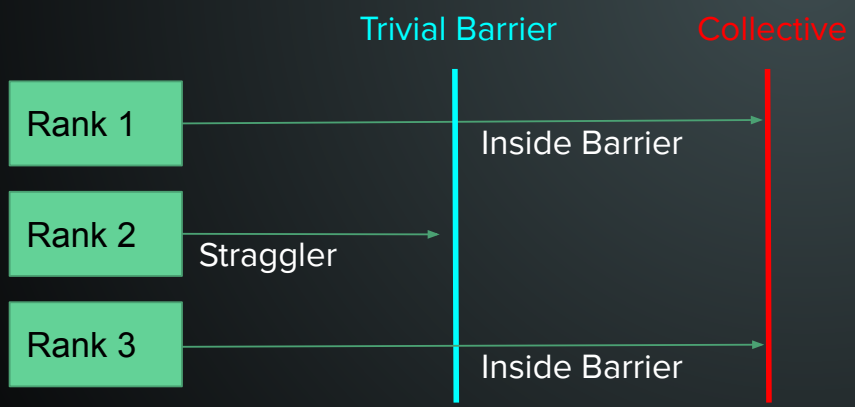


As demonstrated by *Hursey et al.*, abstracting by "MPI Messages" allows for Network Agnosticism.

Checkpointing Collective Operations

Solution: Two-phase collectives

1. Preface all collectives with a trivial barrier
2. When the trivial barrier is completed, call the original collective



Checkpointing Collective Operations

Solution: Two-phase collectives

1. Preface all collectives with a trivial barrier
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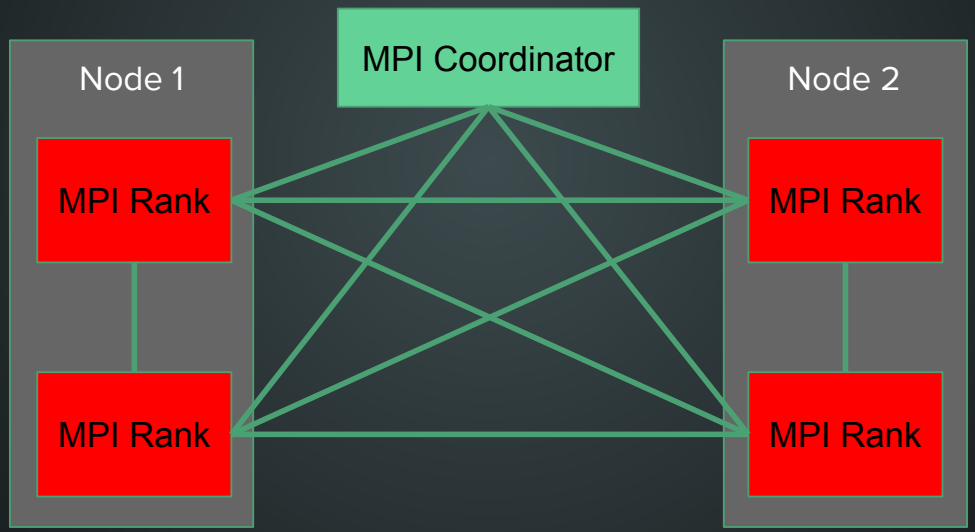
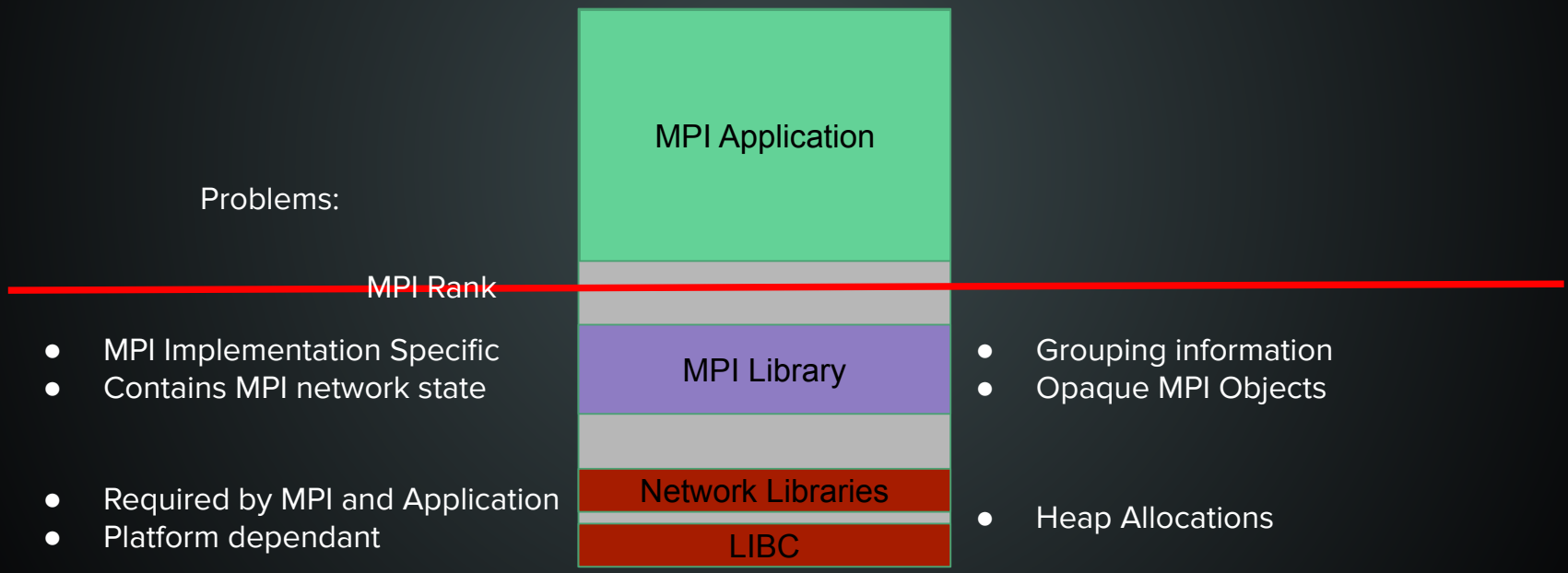
Achieving Agnosticism

Step 2: Discard the network

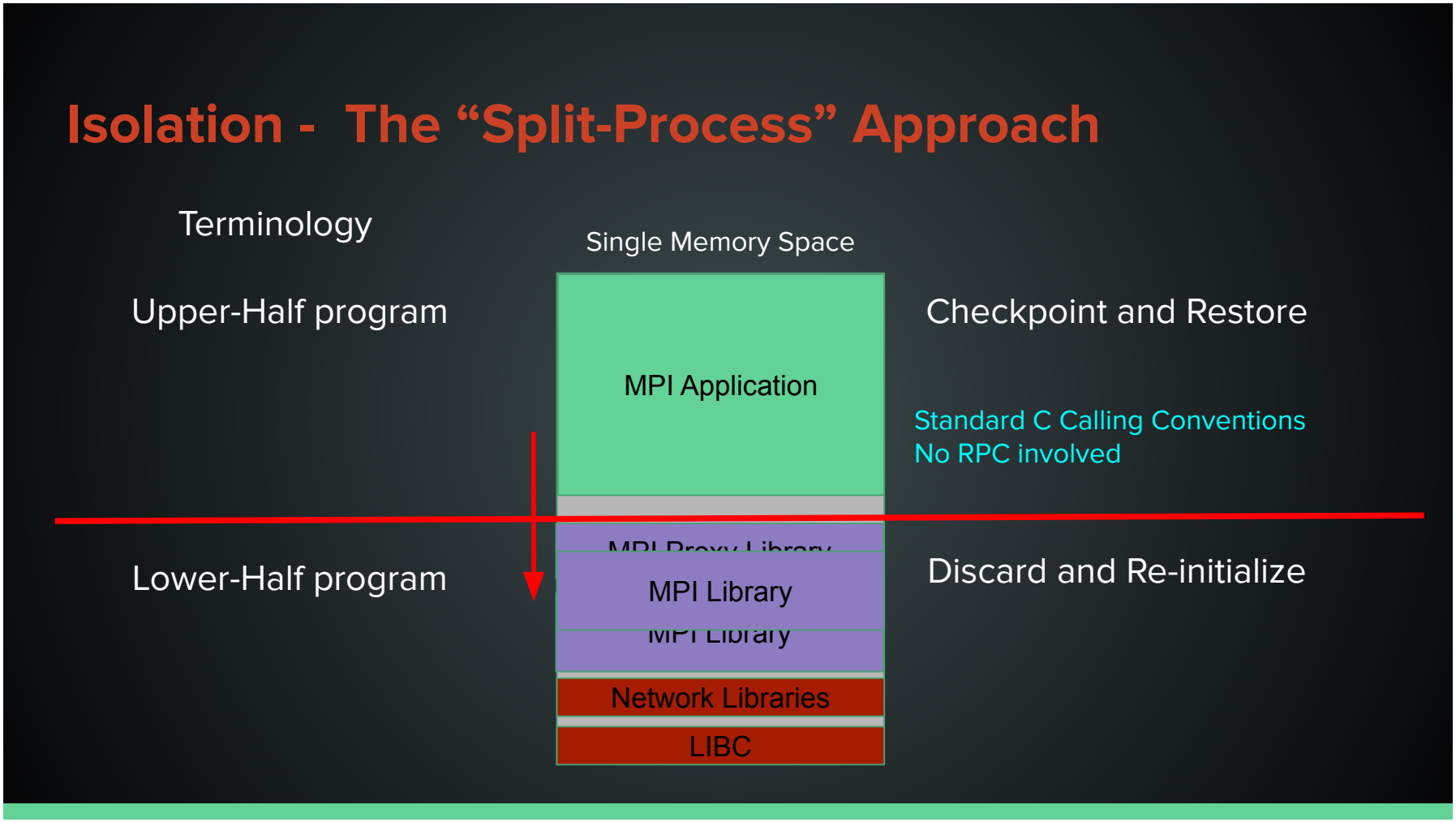


Checkpointing A Rank

Checkpointing the rank is simpler... right?

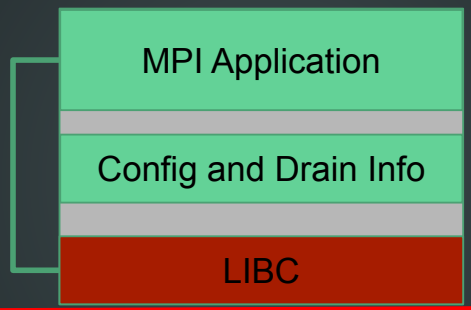


Isolation - The "Split-Process" Approach



MPI Agnosticism Achieved

Upper Half:
Persistent Data



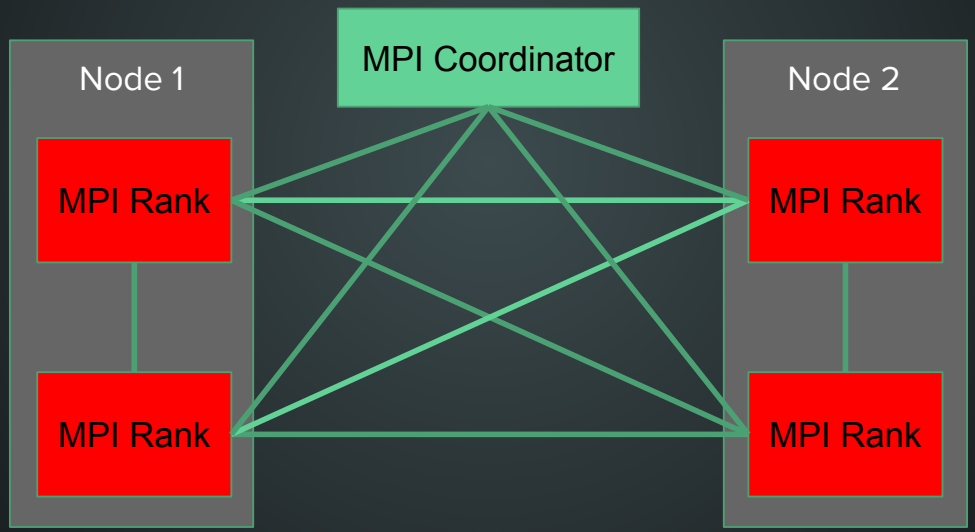
*Special care must be taken when replacing upper half libraries

Lower Half
Ephemeral Data

Lower half data can be replaced by new and different implementations of MPI and related libraries.

Checkpoint Process

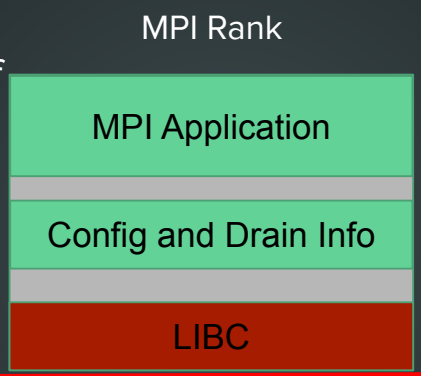
Step 1: Drain the Network



Checkpoint Process

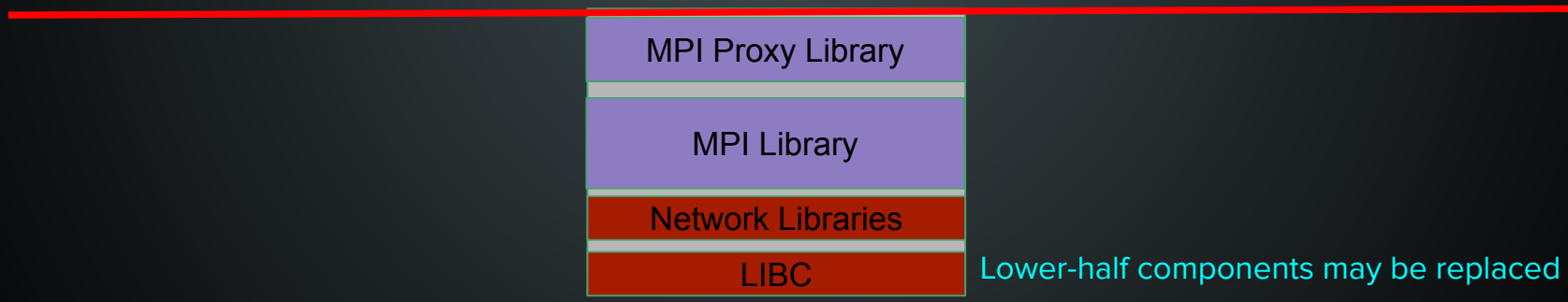
Step 1: Drain the Network

Step 2: Checkpoint Upper-Half



Restart Process

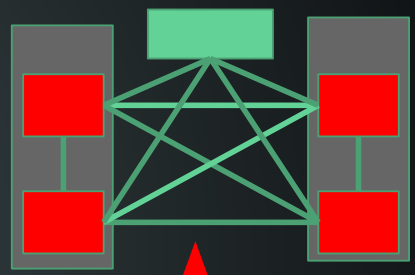
Step 1: Restore Lower-Half



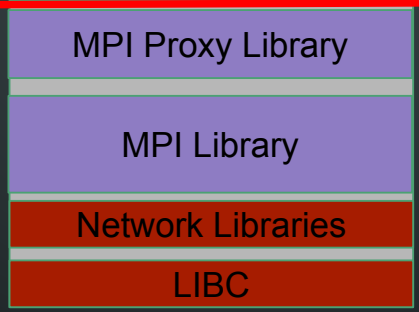
Restart Process

Step 1: Restore Lower-Half

Step 2: Re-initialize MPI



Naturally Optimized

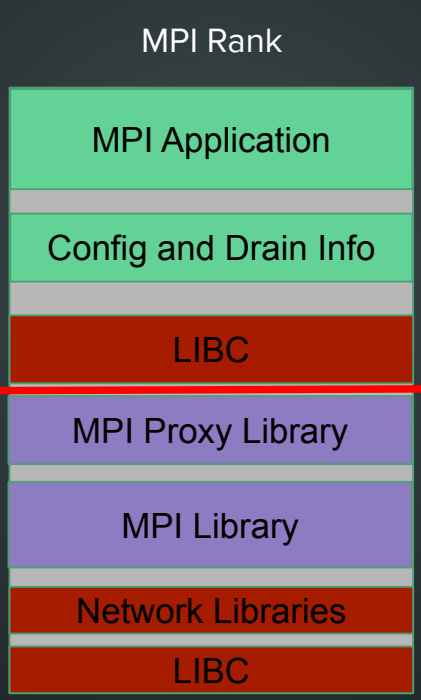


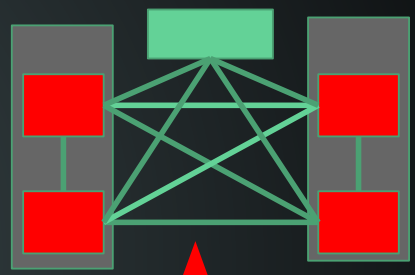
- MPI_INIT
- Replay Configuration

Lower-half components may be replaced

Restart Process

Step 1: Restore Lower-Half
Step 2: Re-initialize MPI
Step 3: Restore Upper-Half





Naturally Optimized

MPI Rank # assigned by MPI_Init used to select checkpoint file for restoring the upper half.

This avoids the need to virtualize MPI Rank numbers.

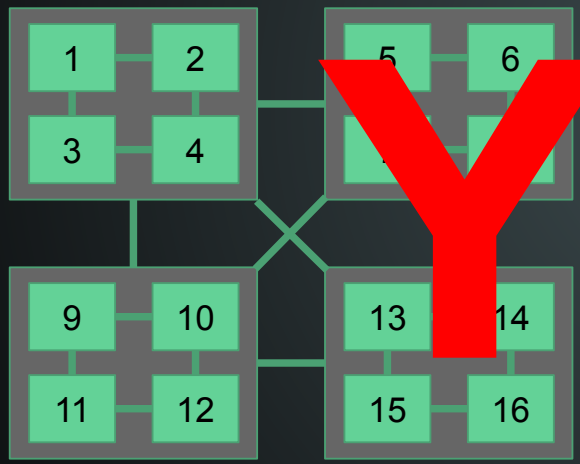
- MPI_INIT
- Replay Configuration

Lower-half components may be replaced

Puzzle

Can you solve checkpointing on...

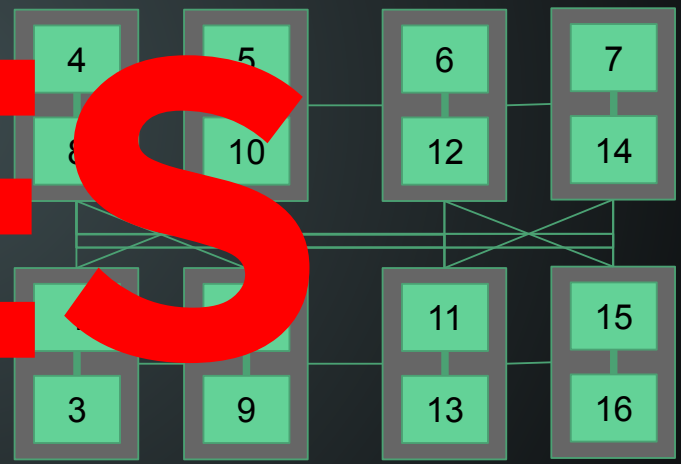
Cray MPI over Infiniband



4 Nodes, 4 Cores/Ranks per Node

And restart on...

MPICH over TCP/IP



8 Nodes, 2 Cores/Ranks per Node

YES

Checkpoint-Restart Overhead

Checkpoint Data Size

- GROMACS - 64 Ranks over 2 Nodes: 5.9GB (and 0.6% runtime overhead)
- HPCG - 2048 ranks over 64 nodes: 4TB (and nearly 0% runtime overhead)
- Largely dominated by memory used by benchmark program.

Checkpoint Time

- Largely dominated by disk-write time
- “Stragglers” - a single rank takes much longer to checkpoint than others.

Restart Time

- MPI state reconstruction represented < 10% of total restart time.

NEW: Cross-Cluster MPI Application Migration

Traditionally, migration across disparate clusters was not feasible.

- Different MPI packages across clusters
- Highly optimized configurations tied to local cluster (Caches, Cores/Node)
- Overhead of checkpointing entire MPI state is prohibitive

Overhead of migrating under MANA:

- 1.6% runtime overhead after migration.*

* Linux kernel's upcoming patch https://lwn.net/Articles/769355/ reduces overhead to 0.6%

Outline

Collective Communication: Can it really work?

1. *If we haven't truly begun ...*
   Maybe some processes have not completed their current computation task. Maybe we'll wait a long time before they reach the collective communication. Maybe we should abort the collective communication, and checkpoint immediately.
   (Aborting the collective communication should be safe. We hope that the lower-half MPI didn't start writing yet into the upper user buffers that were passed as arguments.)
2. *But maybe we have begun and we're in the middle of it ...*
   Maybe all processes have already reached the collective communication, and some of them have begun write persistent changes into the upper half user buffers that were passed in. It's dangerous to abort if we've written to the user's buffer. So, maybe we should finish the collective communication if we've truly begun it. We can checkpoint after that.

What to do??? *(I'm so confused.*  *)*

Checkpointing Collective Operations

Solution: Two-phase collectives

1. Preface all collectives with a trivial barrier
2. When the trivial barrier is completed, call the original collective

Collective Communication: How can it work?

1. Maybe some processes are still in the trivial barrier. But then no processes are in the actual barrier invoked by the application.
   - **Solution:** At restart time, discard any operations in the trivial barrrier from the lower half, and restart the trivial barrier in the new (restarted) lower half MPI library.
2. Maybe some processes are still in the actual barrier invoked by the application. But then no processes are in the trivial barrier.
   - **Solution:** We know that all processes must have reached the collective communication, since they have passed through the trivial barrier. So, just wait until they finish the actual collective communication invoked by the application.
     There will be no delay. All processes have entered the collective communication!

(But see the paper for the formal details:)

"MANA for MPI: *MPI-Agnostic Network-Agnostic* Transparent Checkpointing", by R. Garg, G. Price, and G. Cooperman, *High Performance Distributed Computing* (HPDC'19)

Questions?

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QUESTIONS?