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TEMPI: An Interposed MPI Library with a Canonical Representation of CUDA-aware Datatypes

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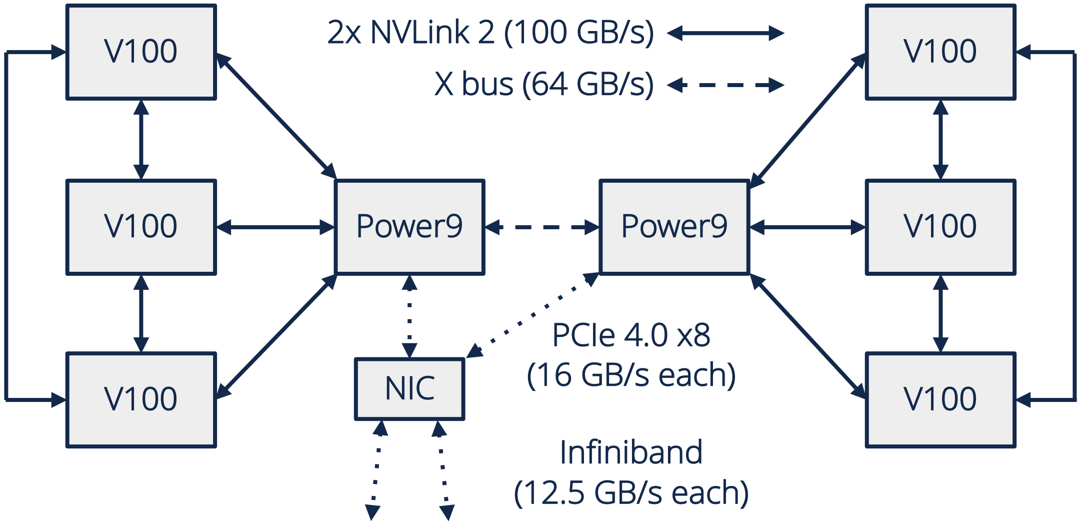
Outline

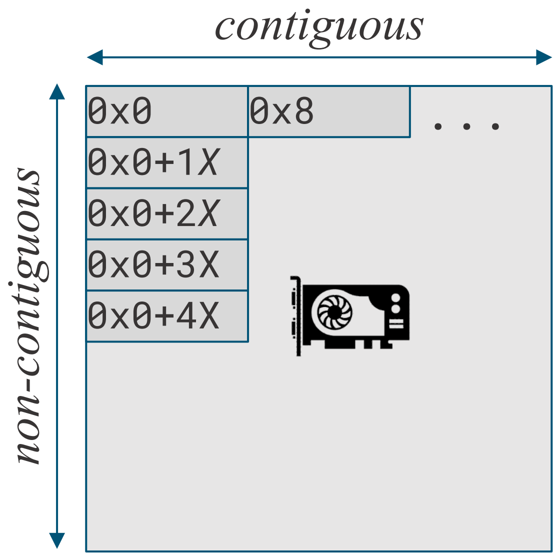
- Distributed GPU stencil, non-contiguous data
- Equivalence of strided datatypes and minimal representation
- GPU communication methods
- Deploying on managed systems
- Large messages and MPI datatypes
- Translation and canonicalization
- Automatic model-driven transfer method selection
- Interposed library implementation

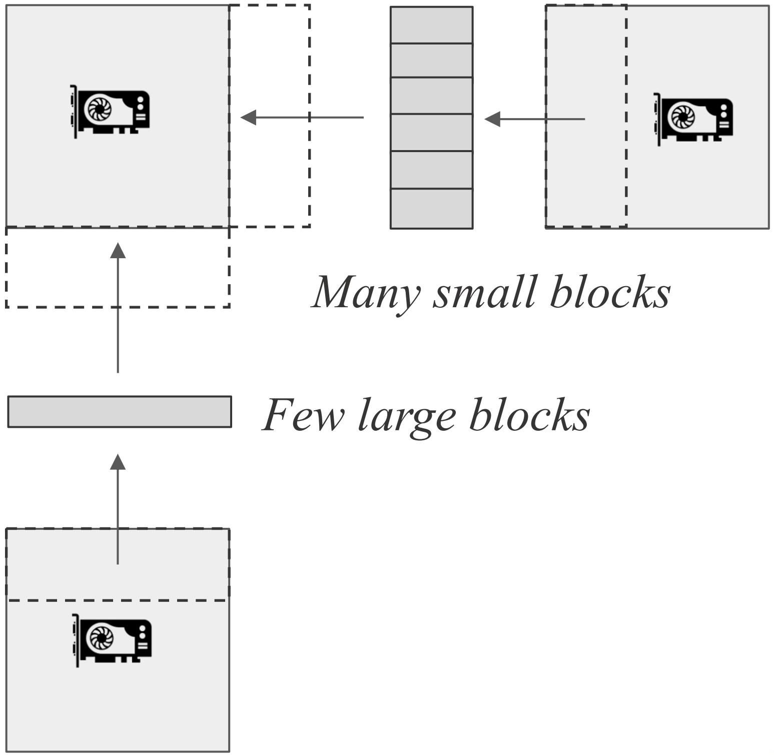
OLCF Summit Node



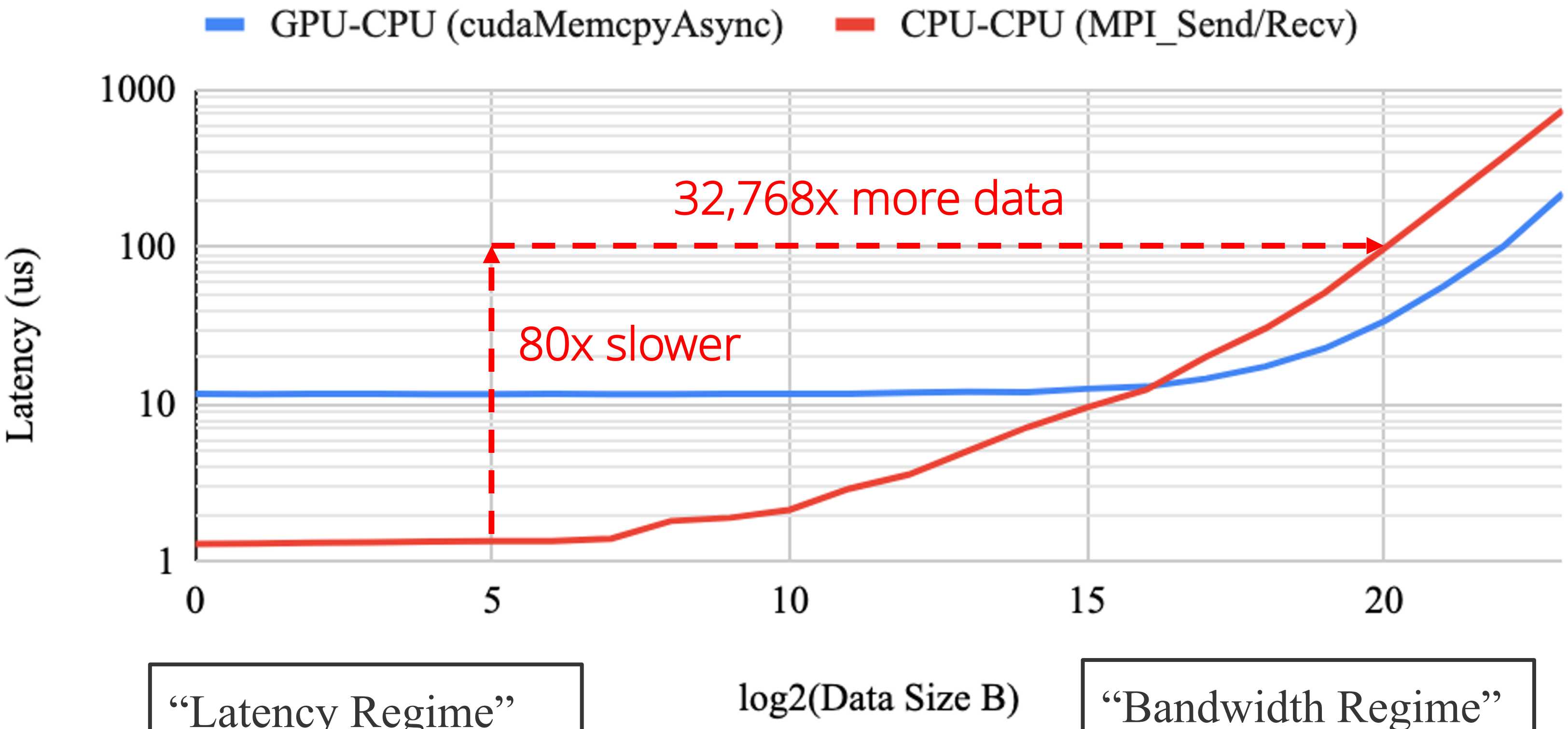
Summit Node
(bidirectional bandwidth)

Stencil Communication and non-contiguous Data





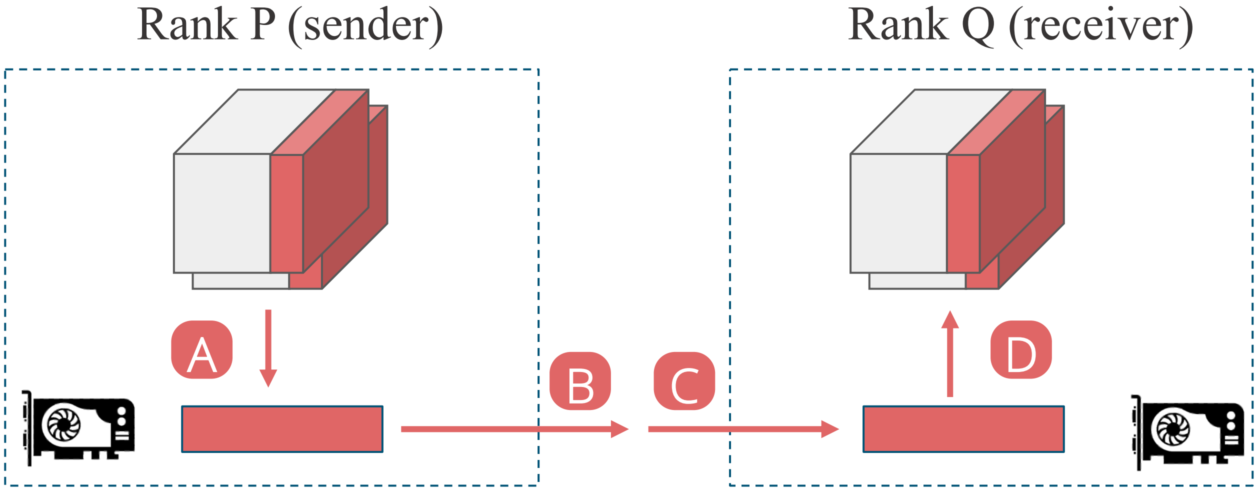
OLCF Summit Latency vs Transfer Size



"Latency Regime"

"Bandwidth Regime"

CUDA-Aware MPI + Packing



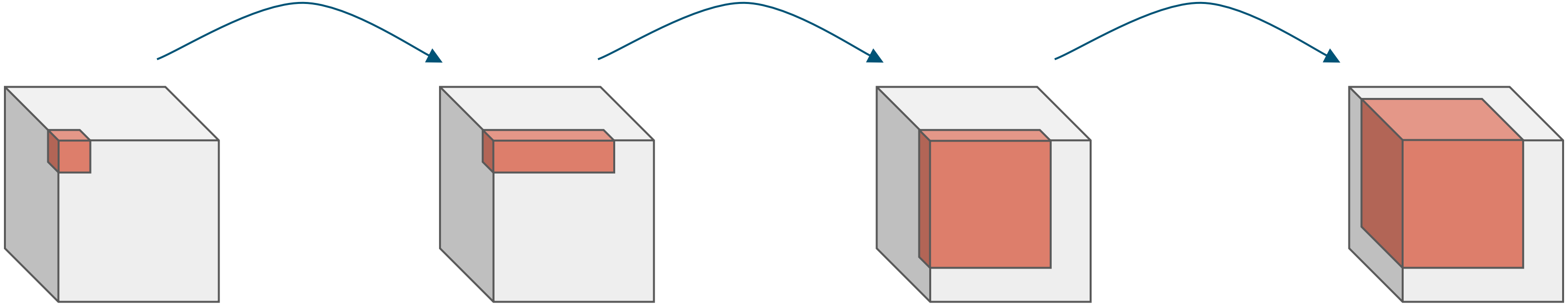
A pack<<<>>>

B MPI_Isend

C MPI_Irecv

D unpack<<<>>>

MPI Derived Datatypes



"MPI_Type_contiguous(…)"

"MPI_Type_vector(…)"

"MPI_Type_vector(…)"

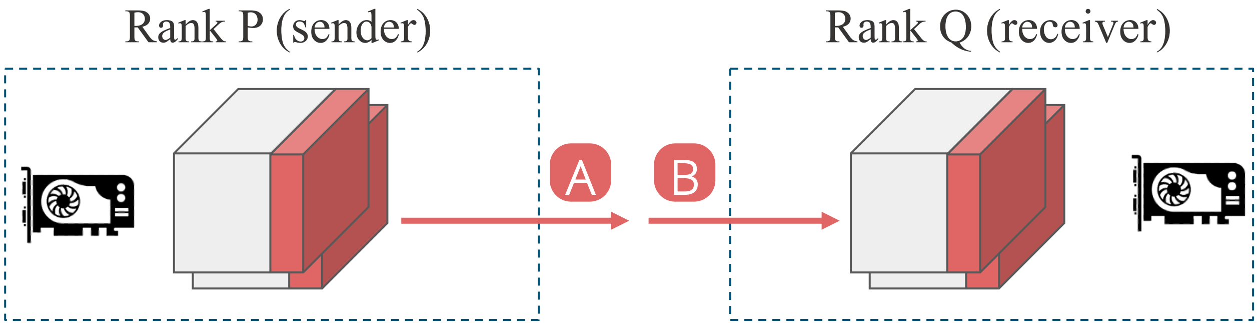
1 MPI_BYTE

row of contiguous bytes

plane of non-contiguous rows

cuboid of non-contigous planes

CUDA-Aware MPI + MPI Derived Datatypes



Setup (once):

Rank P (sender):

```
MPI_Type...
MPI_Type...
...
MPI_Type_commit
```

Rank Q (receiver):

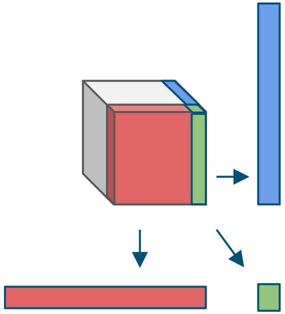
```
MPI_Type...
MPI_Type...
...
MPI_Type_commit
```

Each halo exchange:

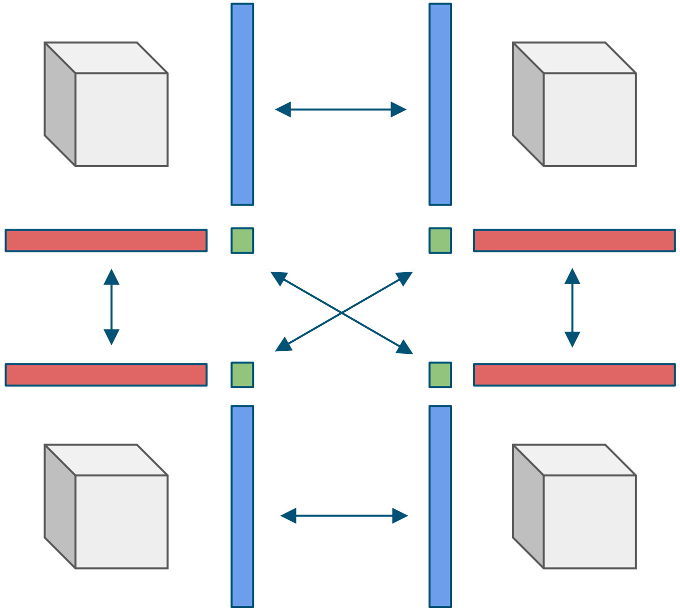
A `MPI_Isend`

B `MPI_Irecv`

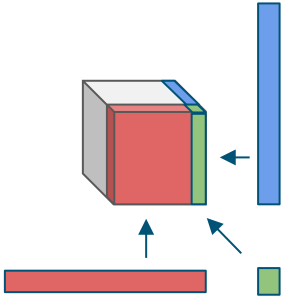
“alltoallv” Halo Exchange



MPI_Packs

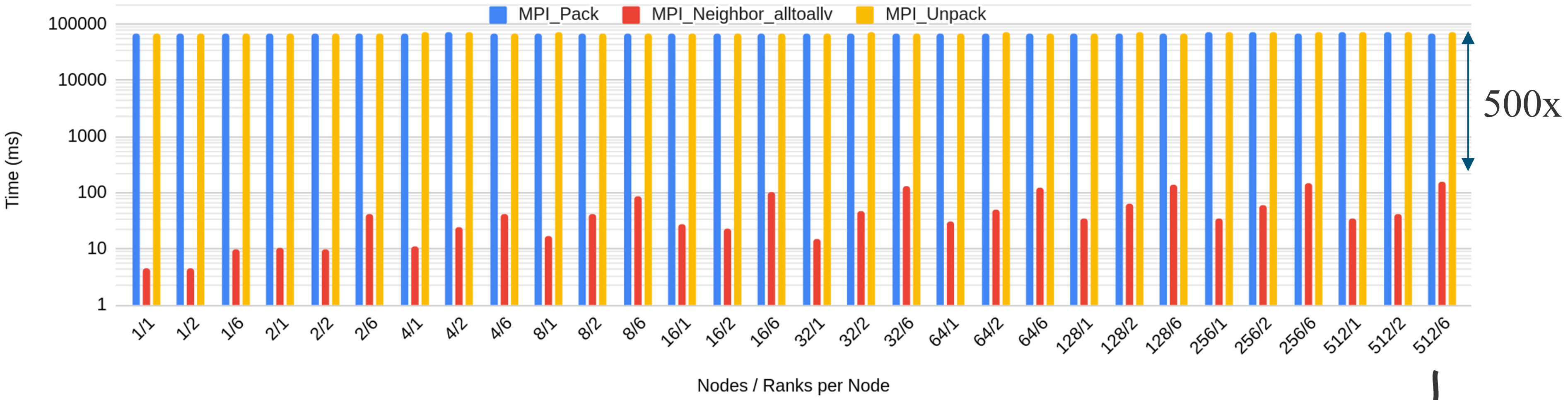


MPI_Neighbor_alltoallv



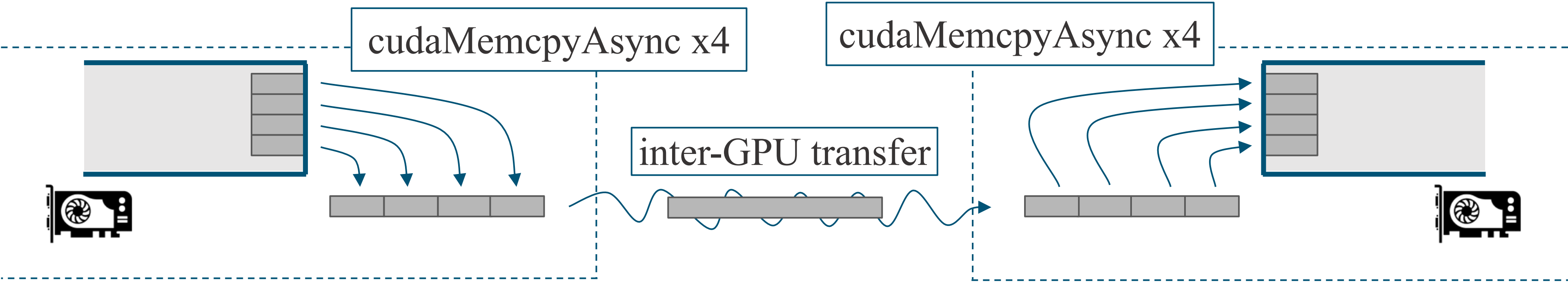
MPI_Unpacks

“alltoallv” with MPI derived types



- MPI_Neighbor_alltoallv = ~500 MB/s/rank
- MPI_Pack / MPI_Unpack = **~1 MB/s**

MPI_Send (Spectrum MPI)



cudaMemcpyAsync x4

inter-GPU transfer

cudaMemcpyAsync x4

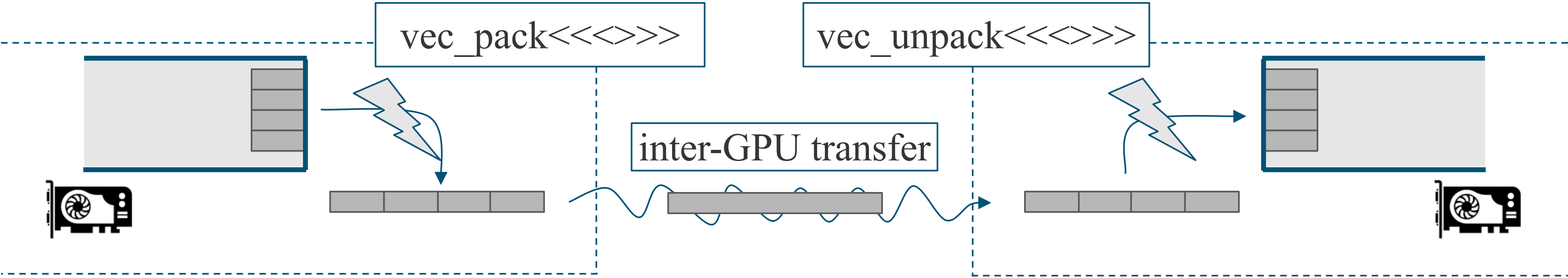
✗ “Latency Regime”

✅ “Bandwidth Regime”

✗ “Latency Regime”

Better MPI_Send (common foundation)

- GPU kernels to pack non-contiguous data



vec_pack<<<>>>

vec_unpack<<<>>>

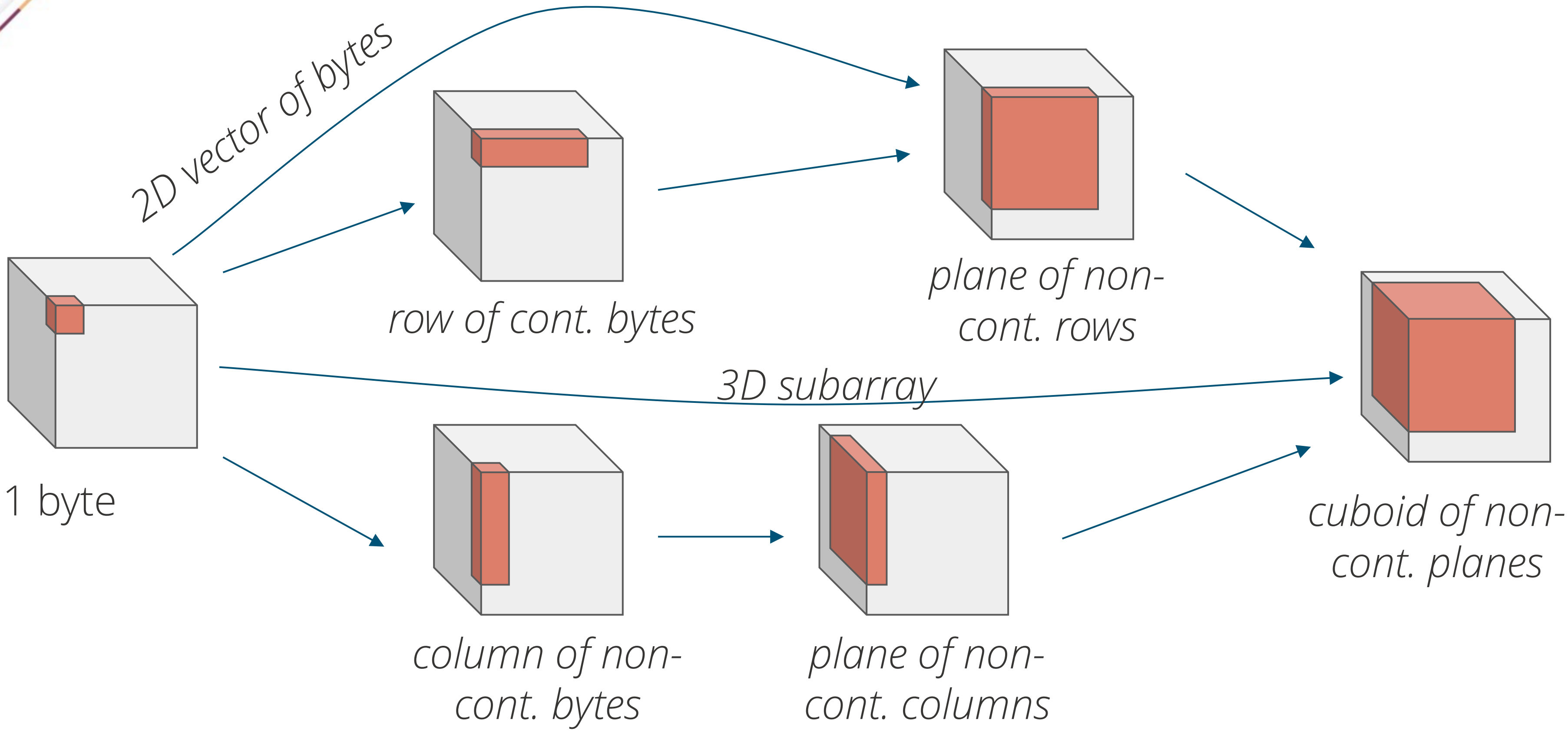
inter-GPU transfer

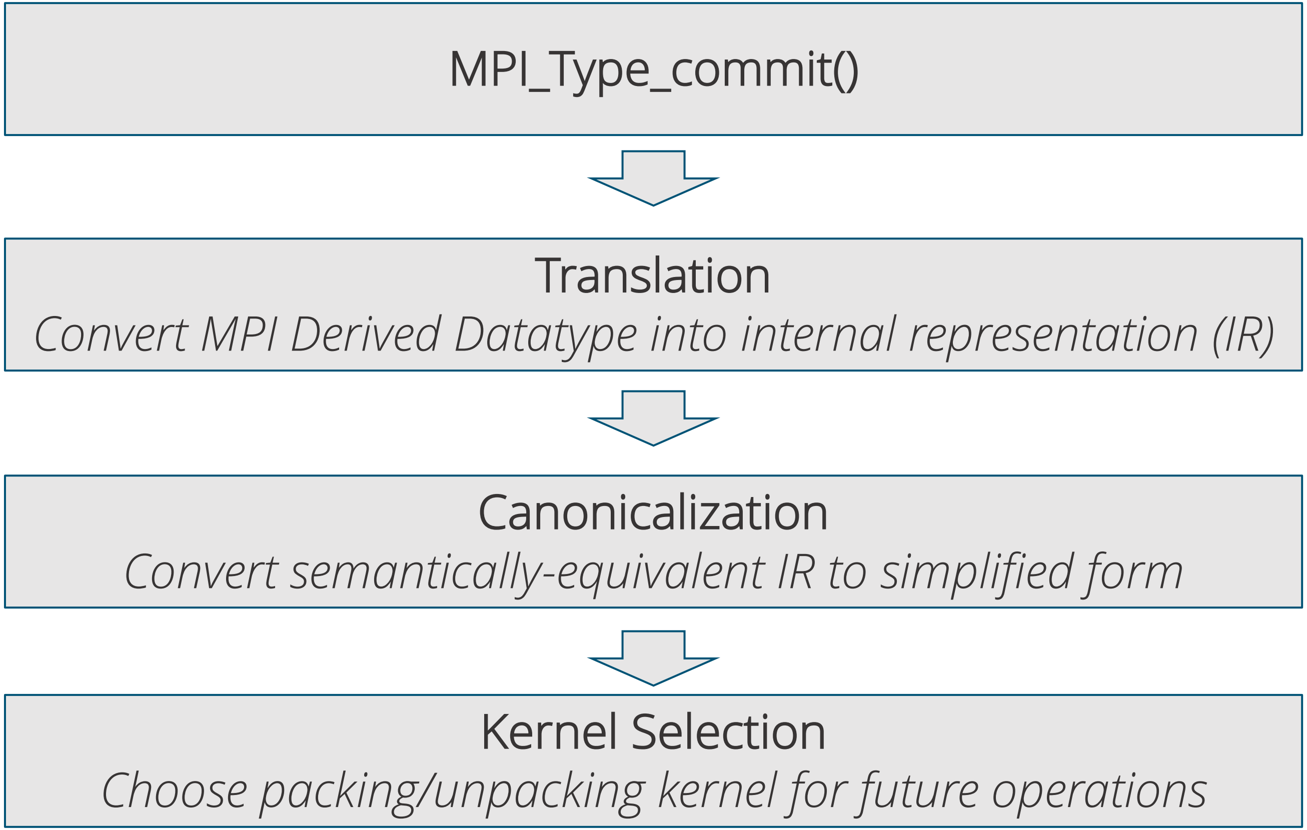
✅ “Bandwidth Regime”

✅ “Bandwidth Regime”

✅ “Bandwidth Regime”

MPI Derived Datatype Equivalence


2D vector of bytes
row of cont. bytes
plane of non-cont. rows
1 byte
3D subarray
cuboid of non-cont. planes
column of non-cont. bytes
plane of non-cont. columns



MPI_Type_commit()

Translation

Convert MPI Derived Datatype into internal representation (IR)

Canonicalization

Convert semantically-equivalent IR to simplified form

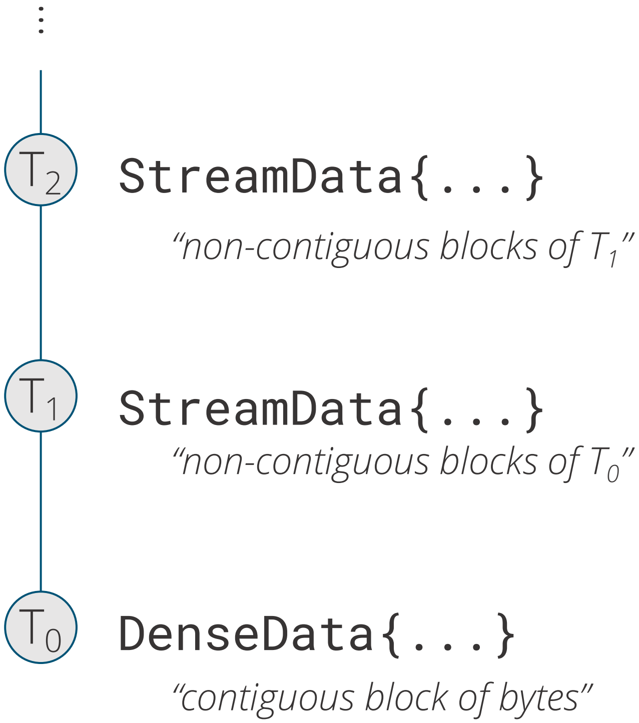
Kernel Selection

Choose packing/unpacking kernel for future operations

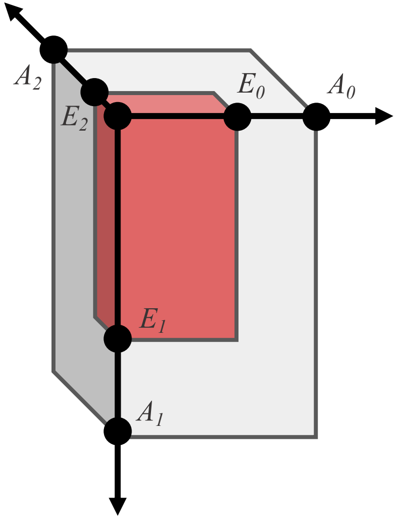
IR - “Internal Representation”

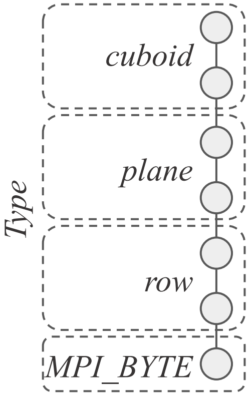
```
StreamData {
  integer offset; // offset (B) of the first element
  integer stride; // pitch (B) between element
  integer count;  // number of elements
}

DenseData {
  integer offset; // offset (B) of the first byte
  integer extent; // number of bytes
}
```

Hierarchy of StreamData, rooted at DenseData


⋮
T_2
StreamData{...}
“non-contiguous blocks of T_1”
T_1
StreamData{...}
“non-contiguous blocks of T_0”
T_0
DenseData{...}
“contiguous block of bytes”

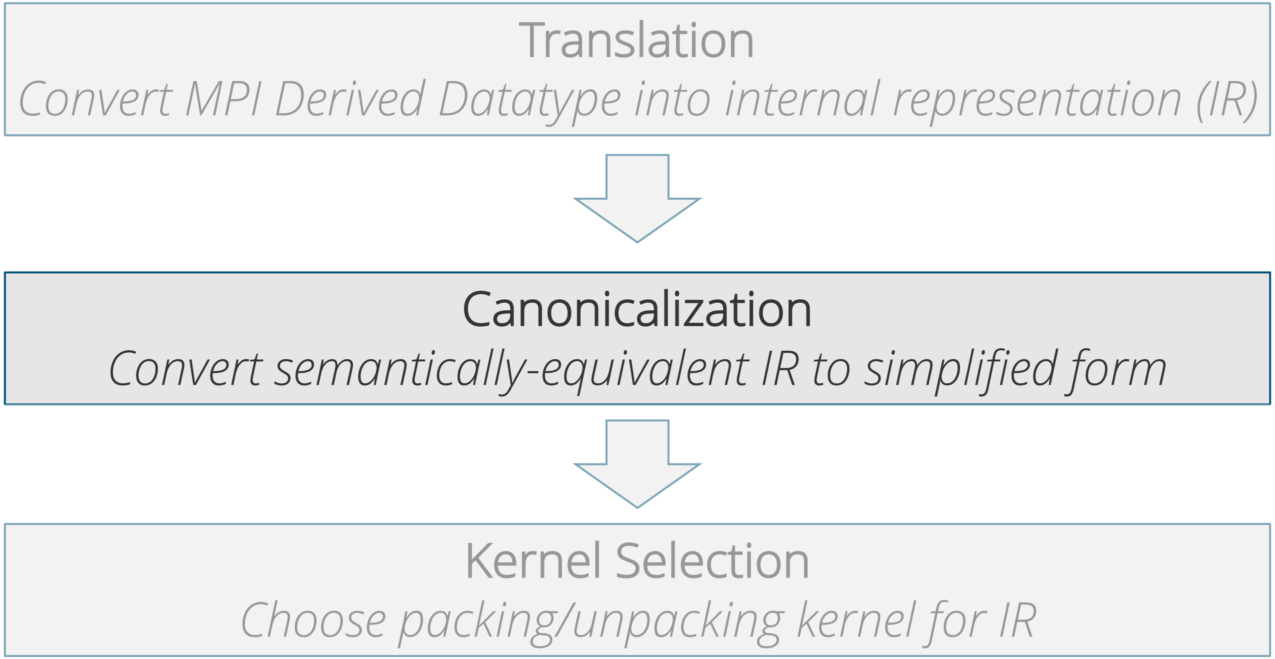
Example





StreamData{offset:0, count:E_2, stride:A_1*A_0}
StreamData{offset:0, count:1, stride:E_1*A_0}
StreamData{offset:0, count:E_1, stride:A_0}
StreamData{offset:0, count:1, stride:E_0}
StreamData{offset:0, count:E_0, stride:1}
StreamData{offset:0, count:1, stride:1}
DenseData{offset:0, extent: 1}

TEMPI Datatype Handling



Translation

Convert MPI Derived Datatype into internal representation (IR)

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Convert semantically-equivalent IR to simplified form

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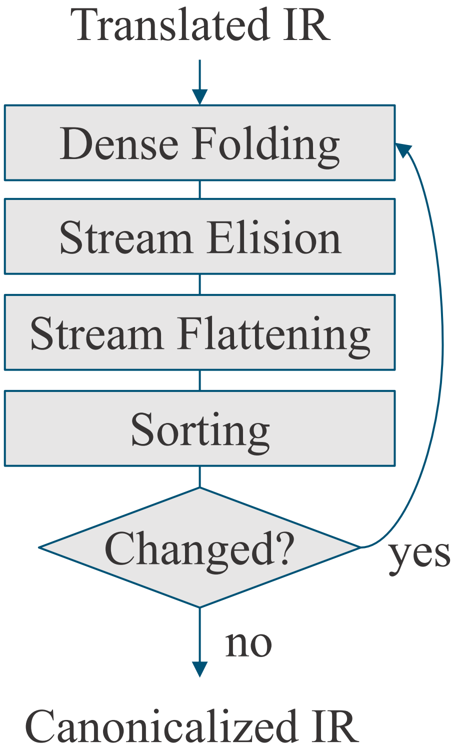
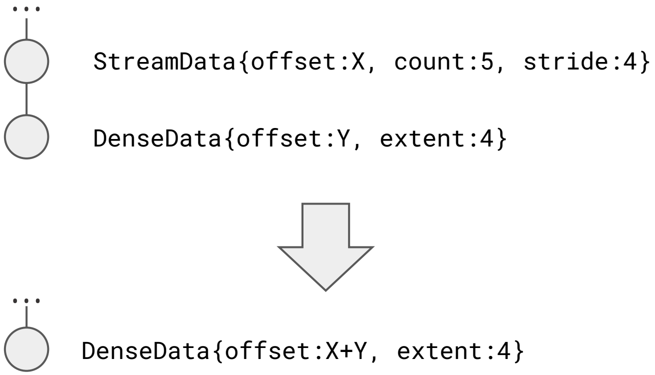
Choose packing/unpacking kernel for IR

Canonicalization



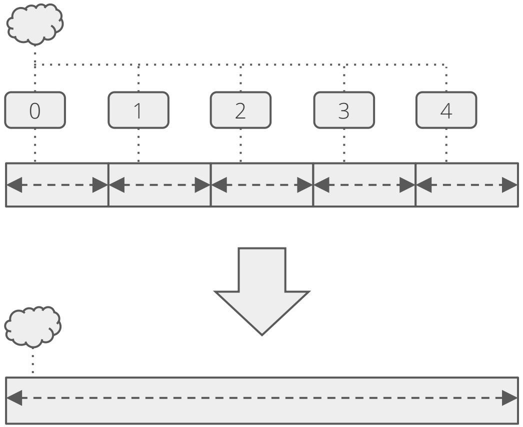
Canonicalization: Dense Folding

- `StreamData` is contiguous `DenseData` (parent of MPI named type)



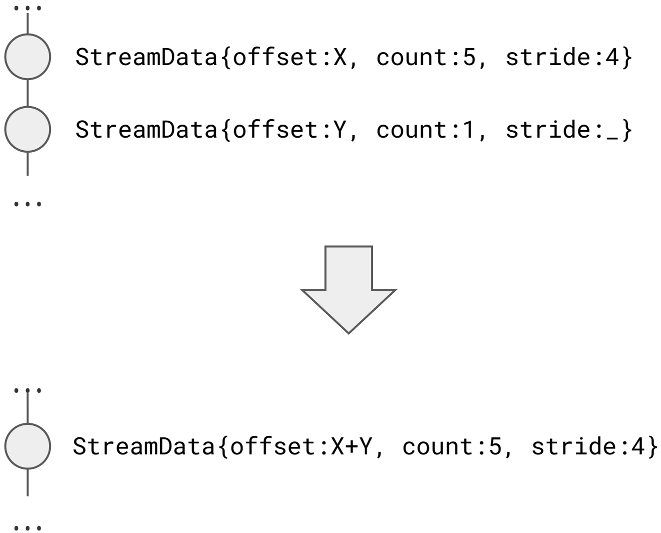
```
...
StreamData{offset:X, count:5, stride:4}
DenseData{offset:Y, extent:4}

...
DenseData{offset:X+Y, extent:4}
```



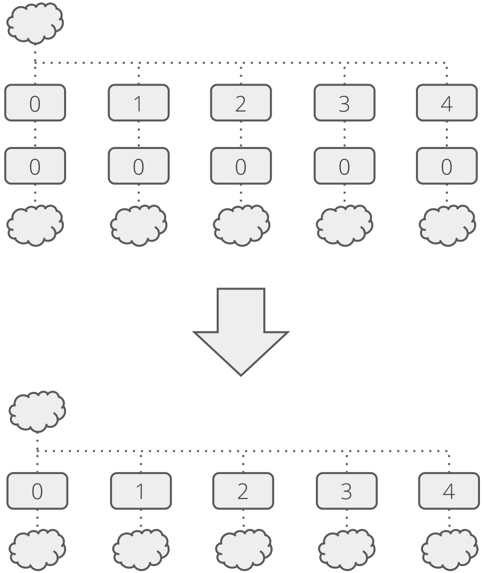
Canonicalization: Stream Elision

- Remove `StreamData` with `count = 1` (MPI Vector blocks commonly have one element)



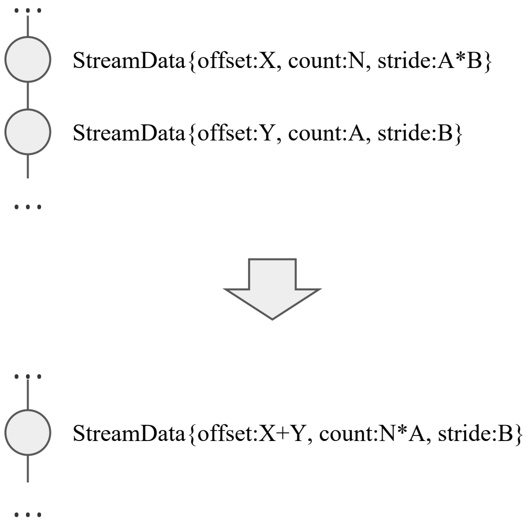
```
StreamData{offset:X, count:5, stride:4}
StreamData{offset:Y, count:1, stride:_}
```

```
StreamData{offset:X+Y, count:5, stride:4}
```



Canonicalization: Stream Flattening

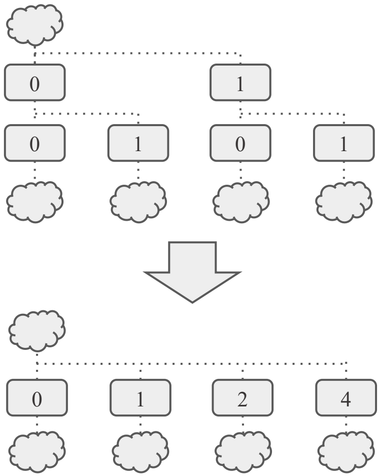
- e.g. two vectors of three vs. one vector of six



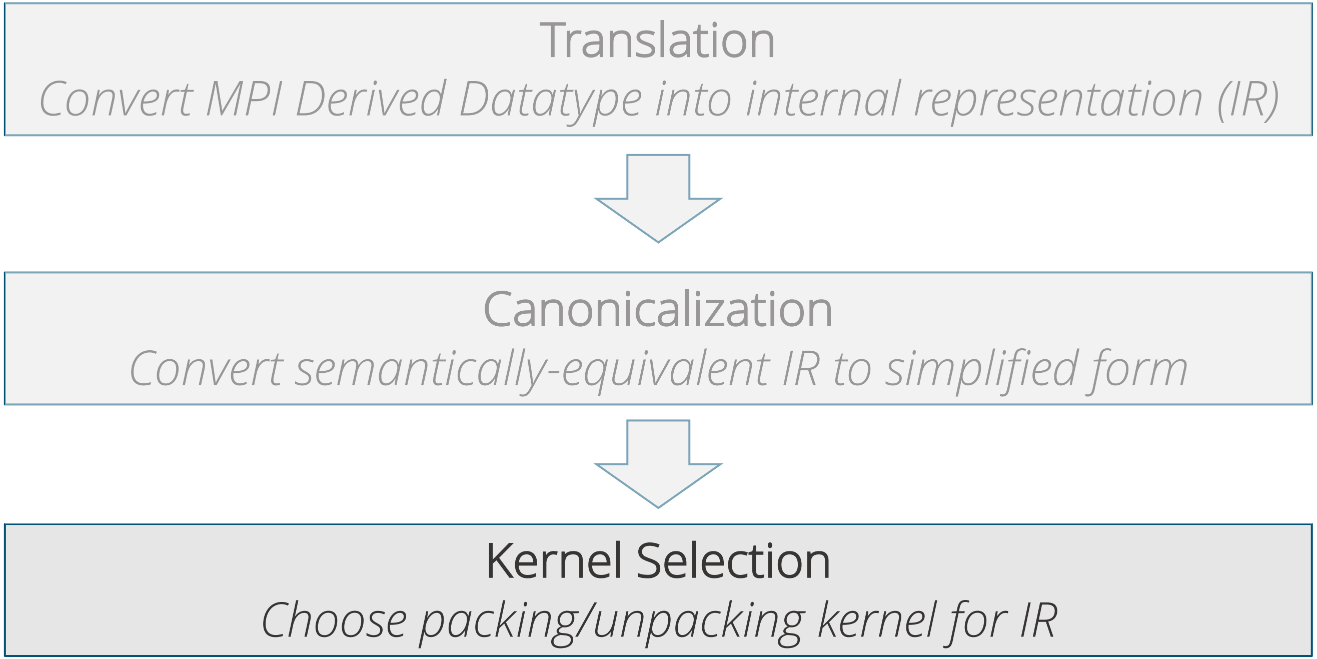
StreamData{offset:X, count:N, stride:A*B}

StreamData{offset:Y, count:A, stride:B}

StreamData{offset:X+Y, count:N*A, stride:B}



TEMPI Datatype Handling



Translation

Convert MPI Derived Datatype into internal representation (IR)

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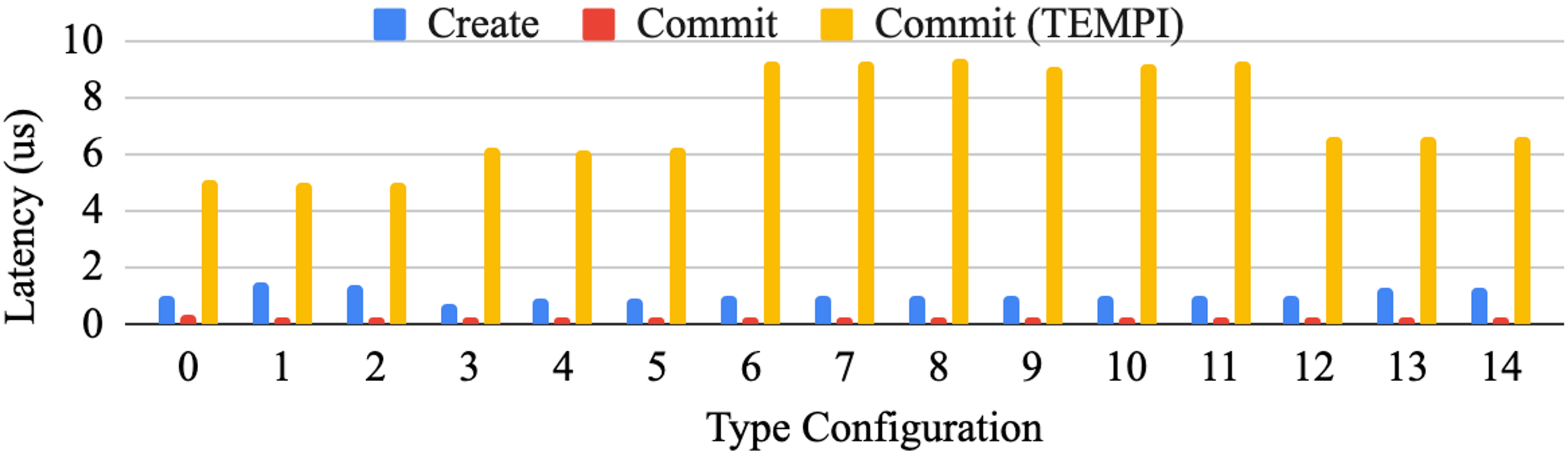
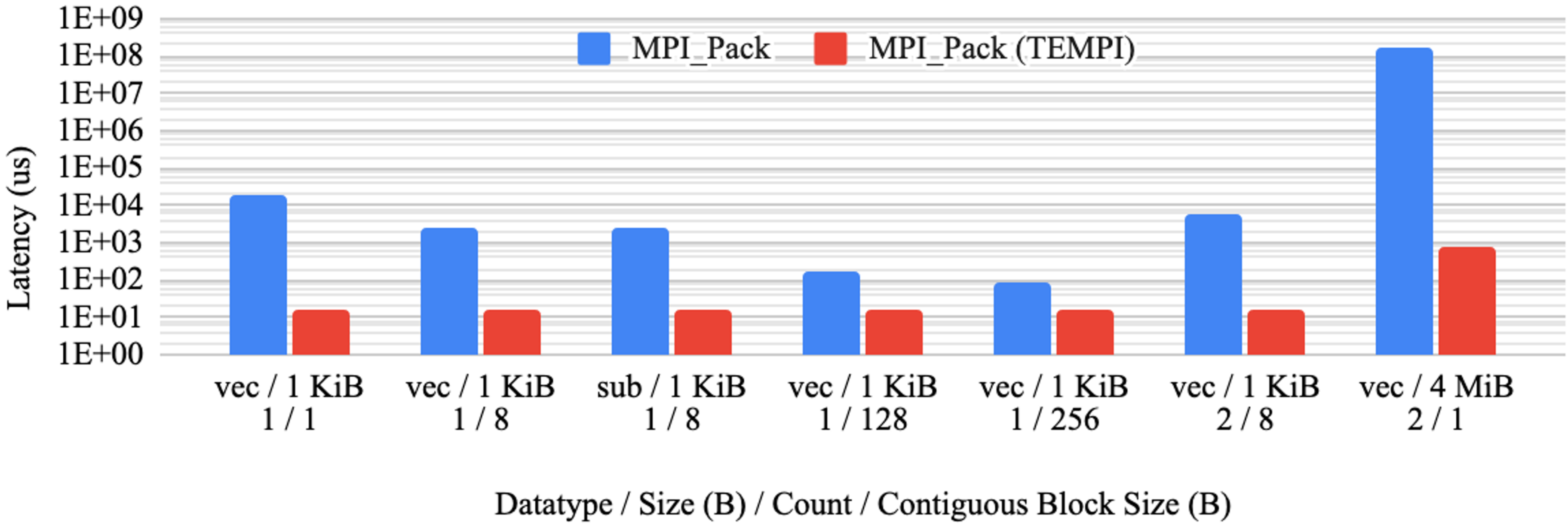
Choose packing/unpacking kernel for IR

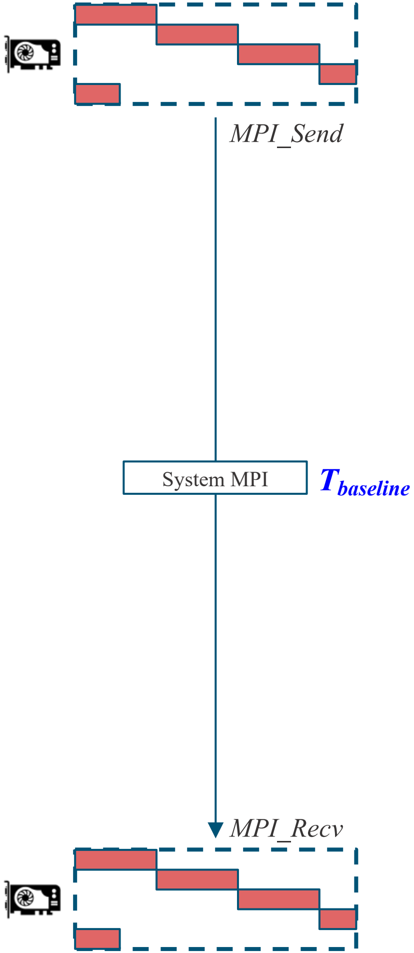
MPI_Type_commit Time



MPI_Pack Results

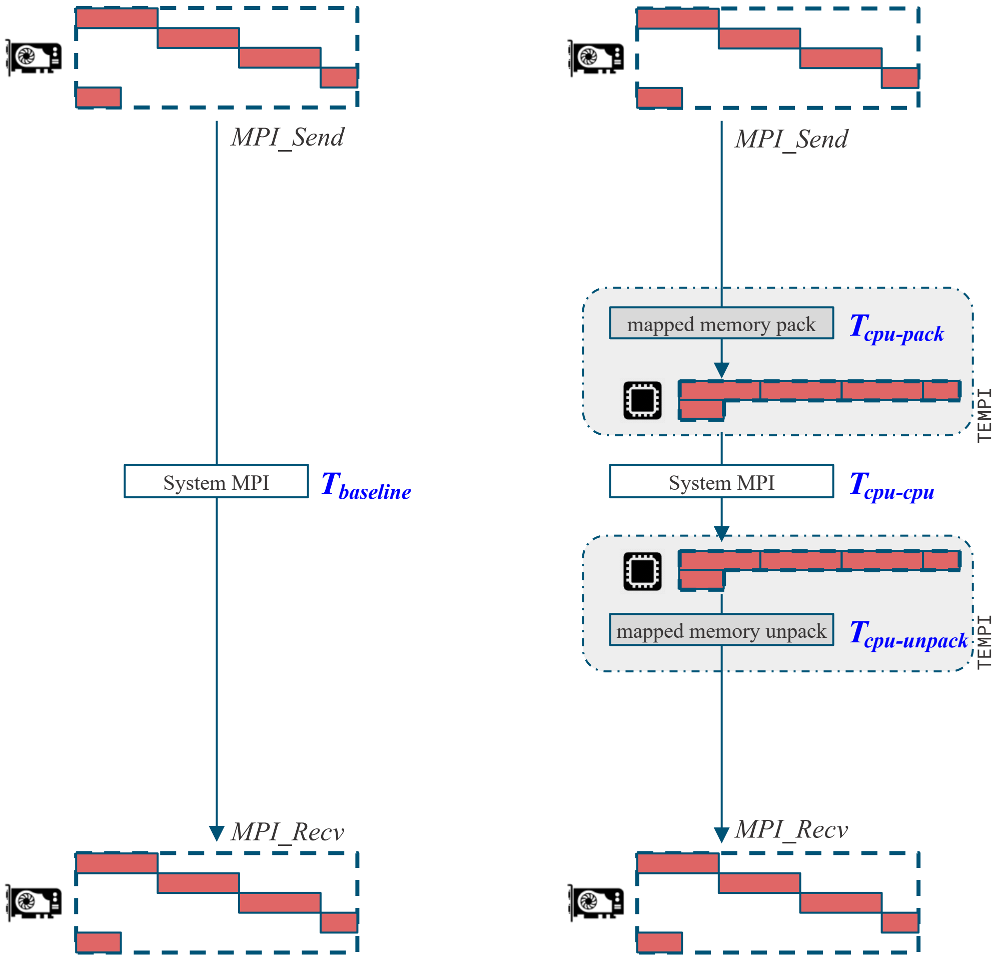


CUDA-Aware System MPI



CUDA-Aware System MPI

TEMPI “One-shot”



MPI_Send

System MPI $T_{baseline}$

MPI_Recv

MPI_Send

mapped memory pack $T_{cpu\text{-}pack}$

TEMPI

System MPI $T_{cpu\text{-}cpu}$

mapped memory unpack $T_{cpu\text{-}unpack}$

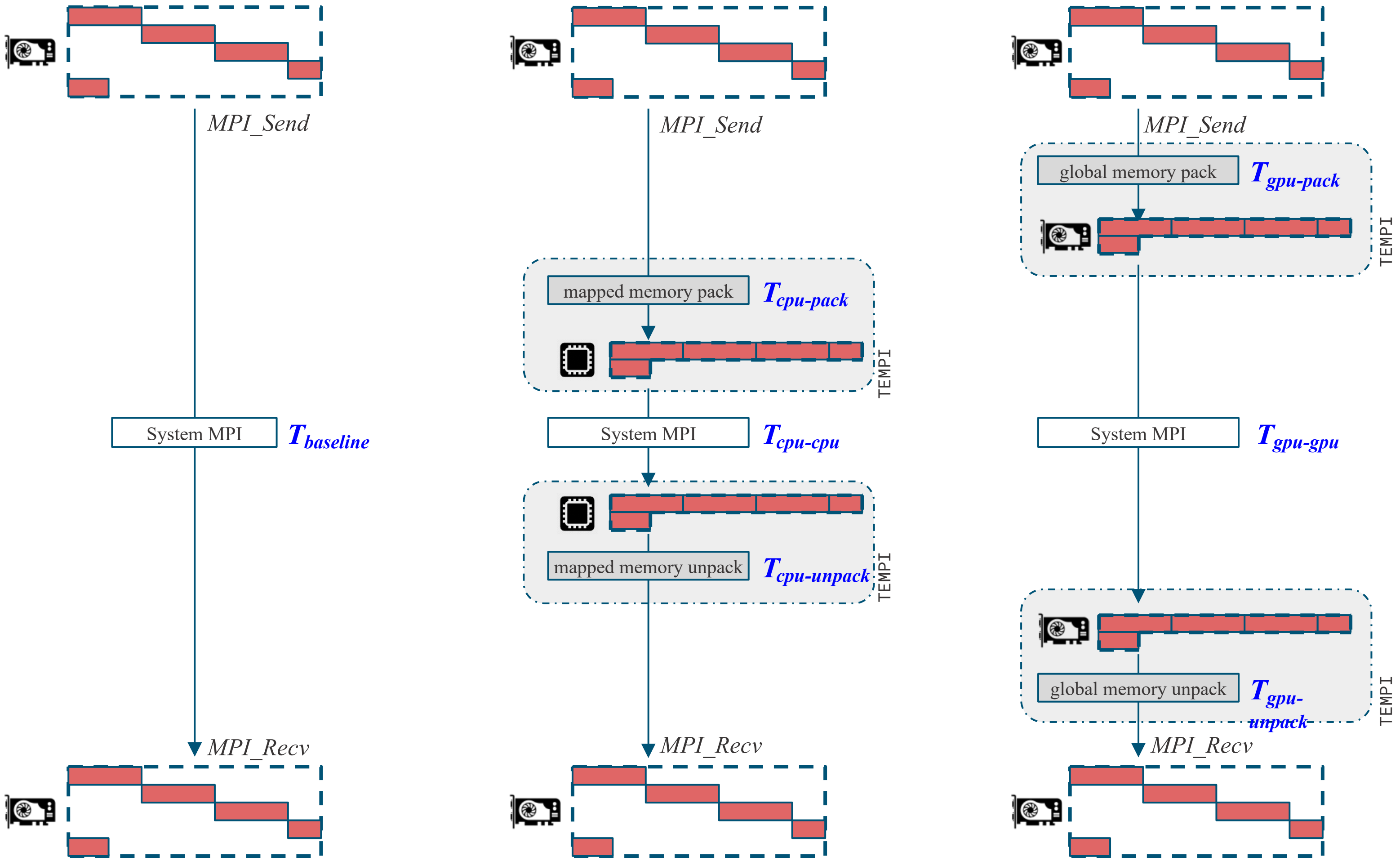
TEMPI

MPI_Recv

CUDA-Aware System MPI

TEMPI "One-shot"

TEMPI "Device"



MPI_Send

System MPI $T_{baseline}$

MPI_Recv

MPI_Send

mapped memory pack $T_{cpu-pack}$

TEMPI

System MPI $T_{cpu-cpu}$

mapped memory unpack $T_{cpu-unpack}$

TEMPI

MPI_Recv

MPI_Send

global memory pack $T_{gpu-pack}$

TEMPI

System MPI $T_{gpu-gpu}$

global memory unpack $T_{gpu-unpack}$

TEMPI

MPI_Recv

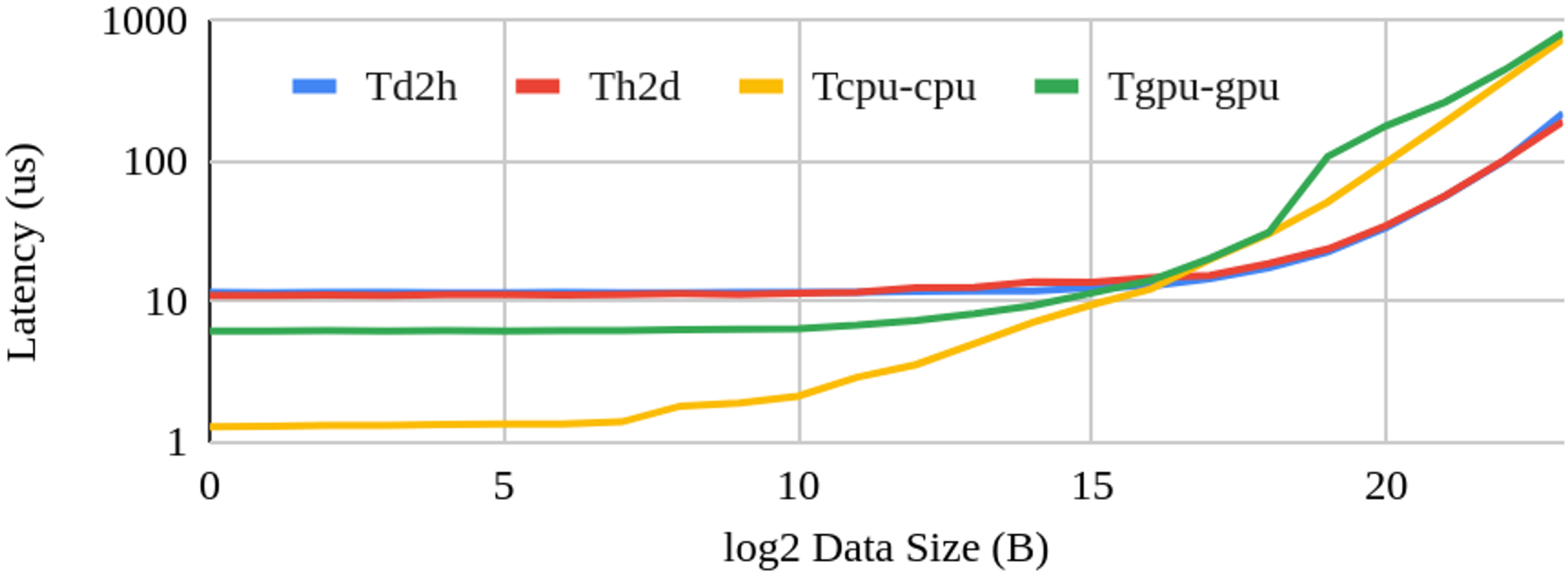
Performance Modeling

$$T_{device} = T_{gpu-pack} + T_{gpu-gpu} + T_{gpu-unpack}$$

$$T_{oneshot} = T_{host-pack} + T_{cpu-cpu} + T_{host-unpack}$$

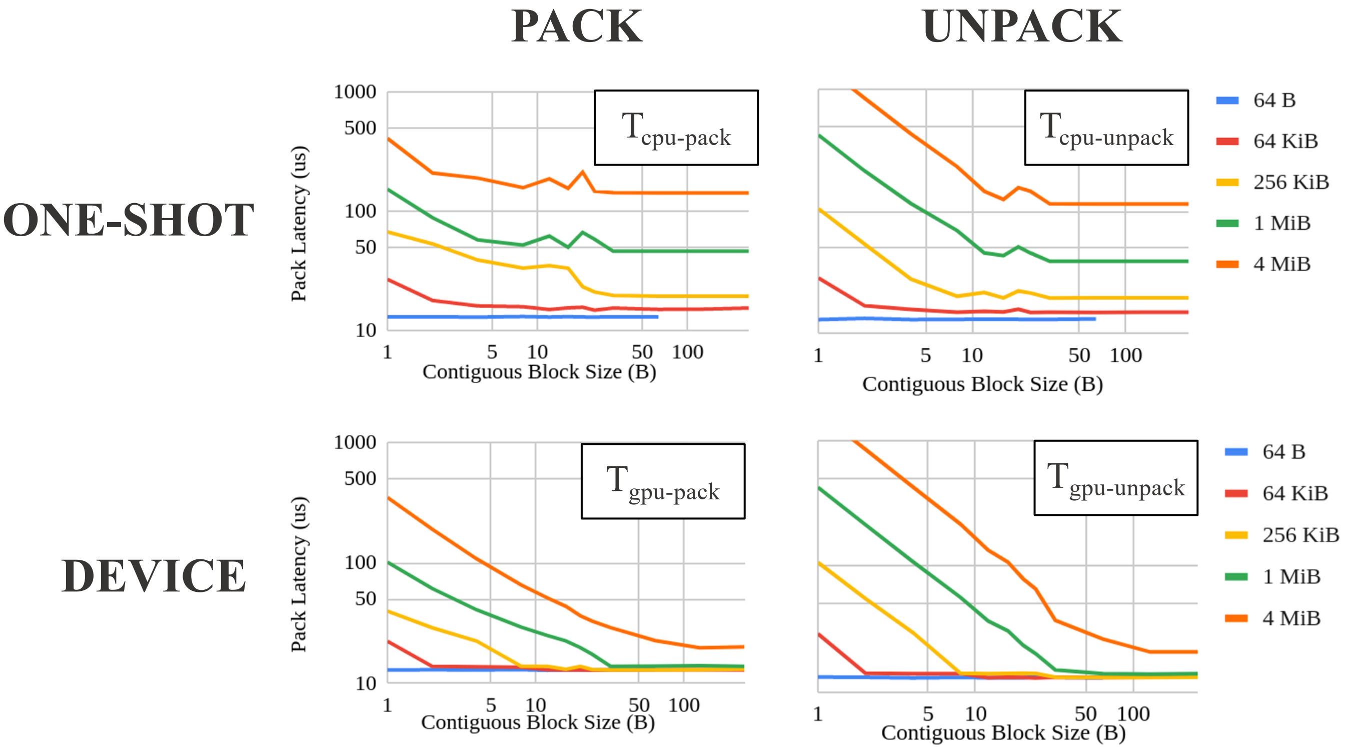
$$T_{staged} = T_{gpu-pack} + T_{d2h} + T_{cpu-cpu} + T_{h2d} + T_{gpu-unpack}$$

Contiguous Transfer Measurements



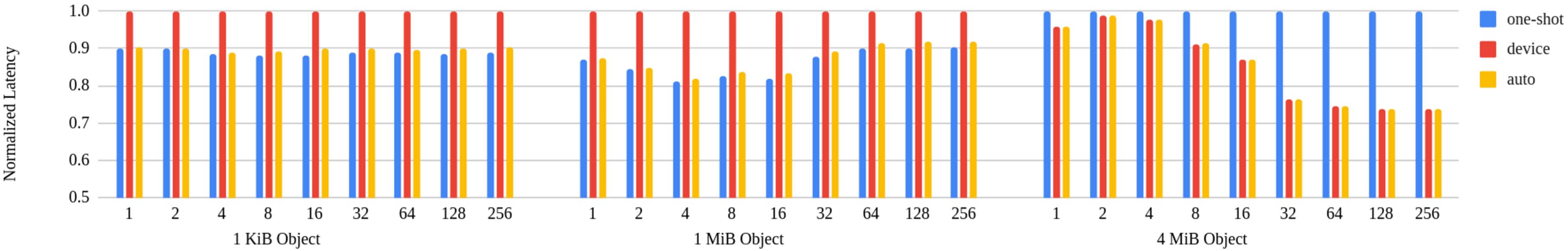
T depends on # bytes transferred

One-shot and Device Pack and Unpack



T depends on object size and block size

MPI_Send Microbenchmark

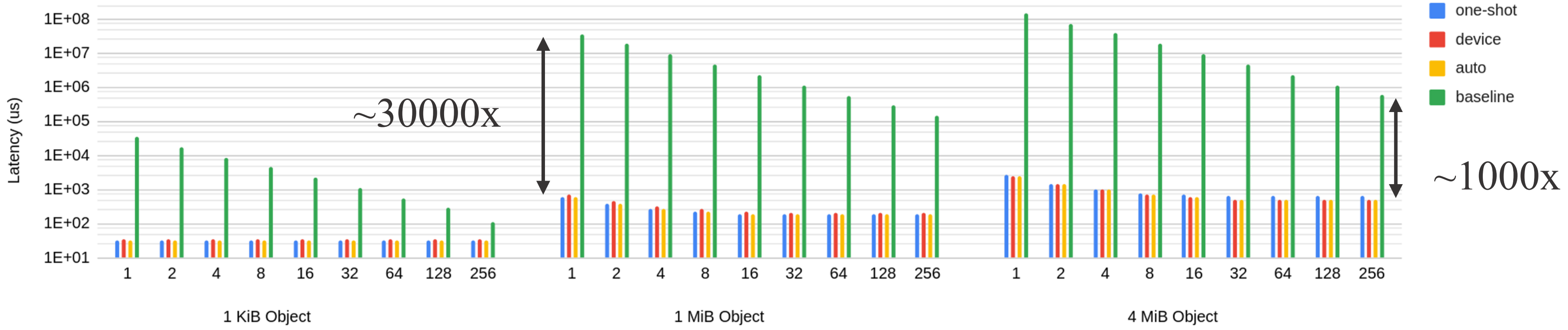


Minimal runtime performance-modeling overhead

Performance model reliably chooses faster method

MPI_Send / MPI_Recv

MPI_Send/Recv Latency for 2D objects with different block sizes



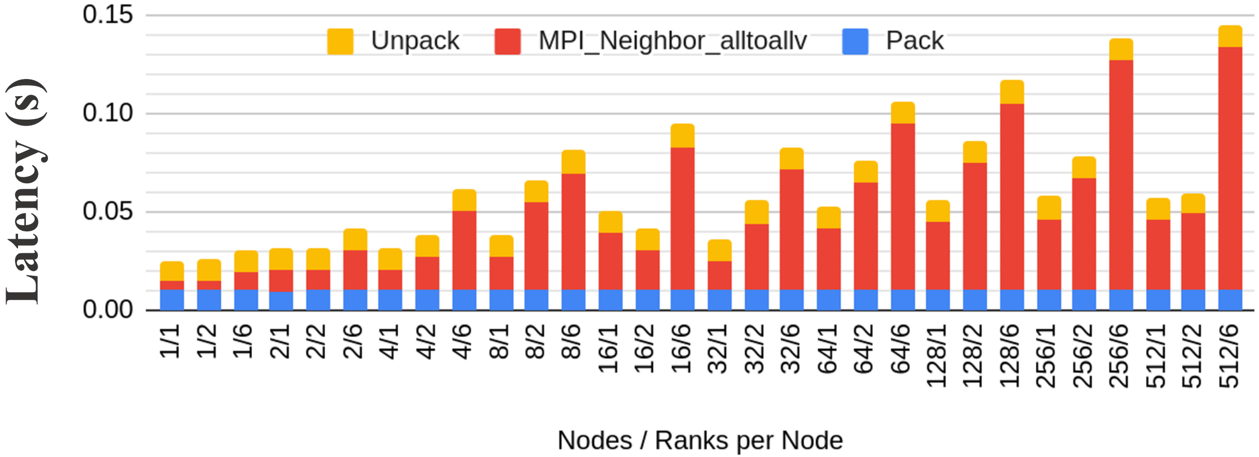
~30000x

~1000x

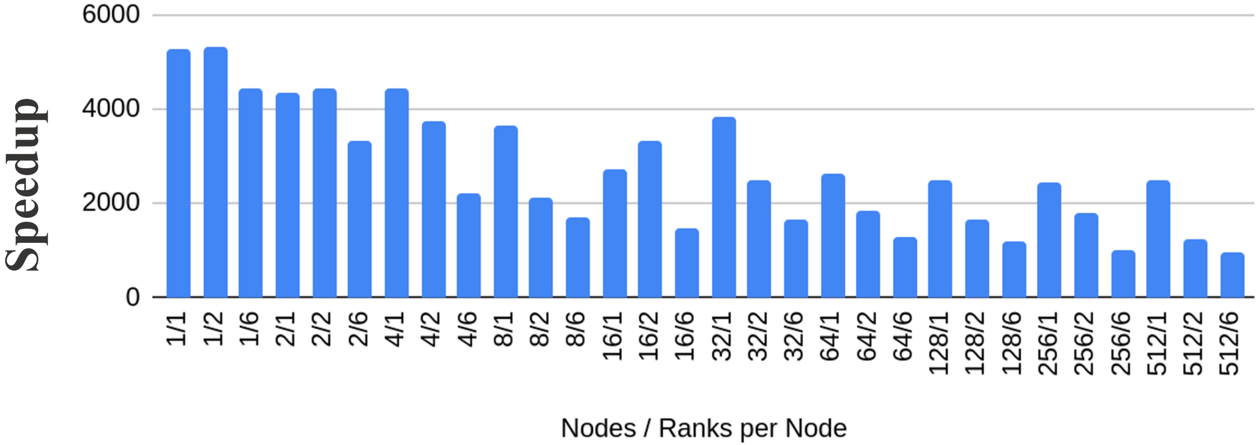
Large latency improvement from datatype handling
Small additional improvement from automatic method selection

Halo Exchange

With TEMPI, non-contiguous packing no longer dominates



Large speedup in 3D halo exchange

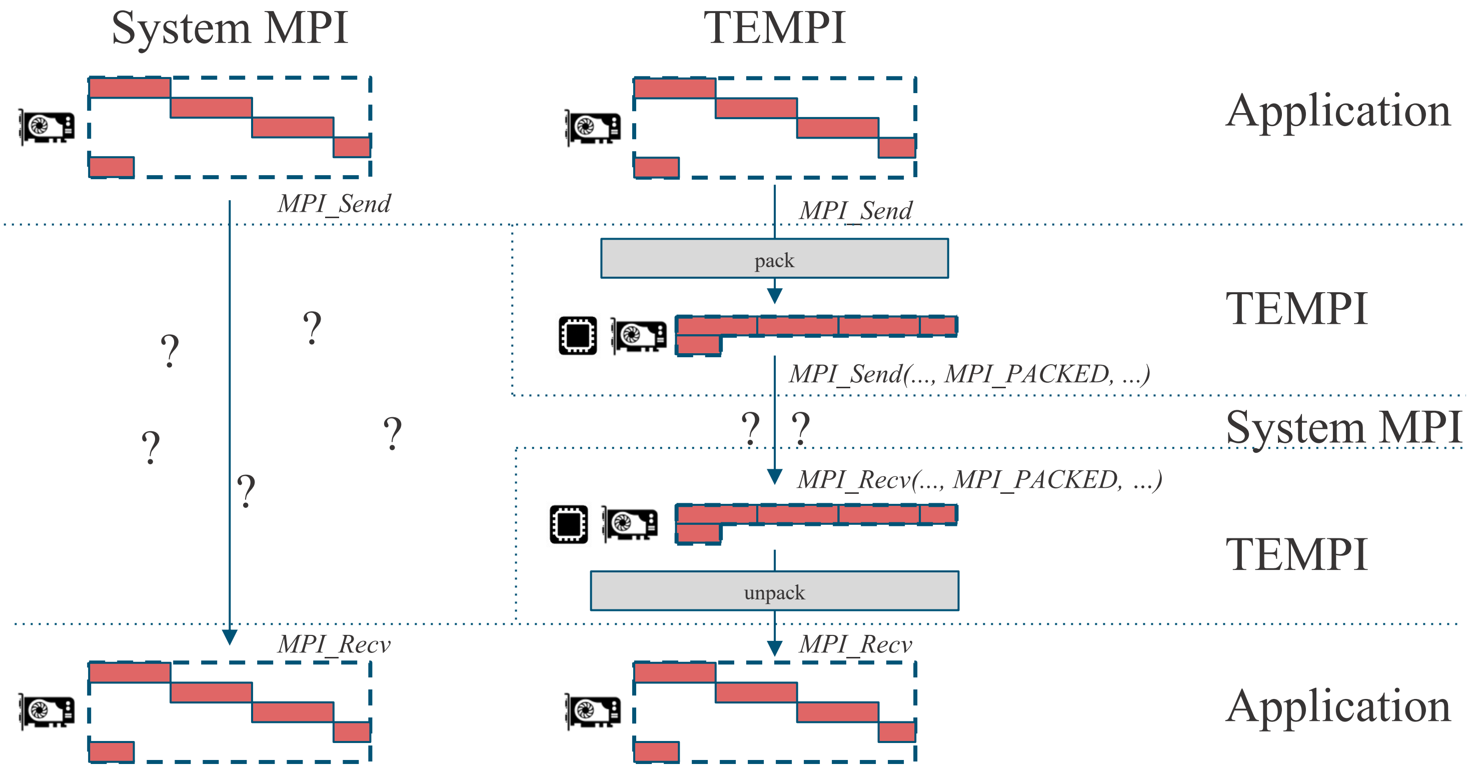


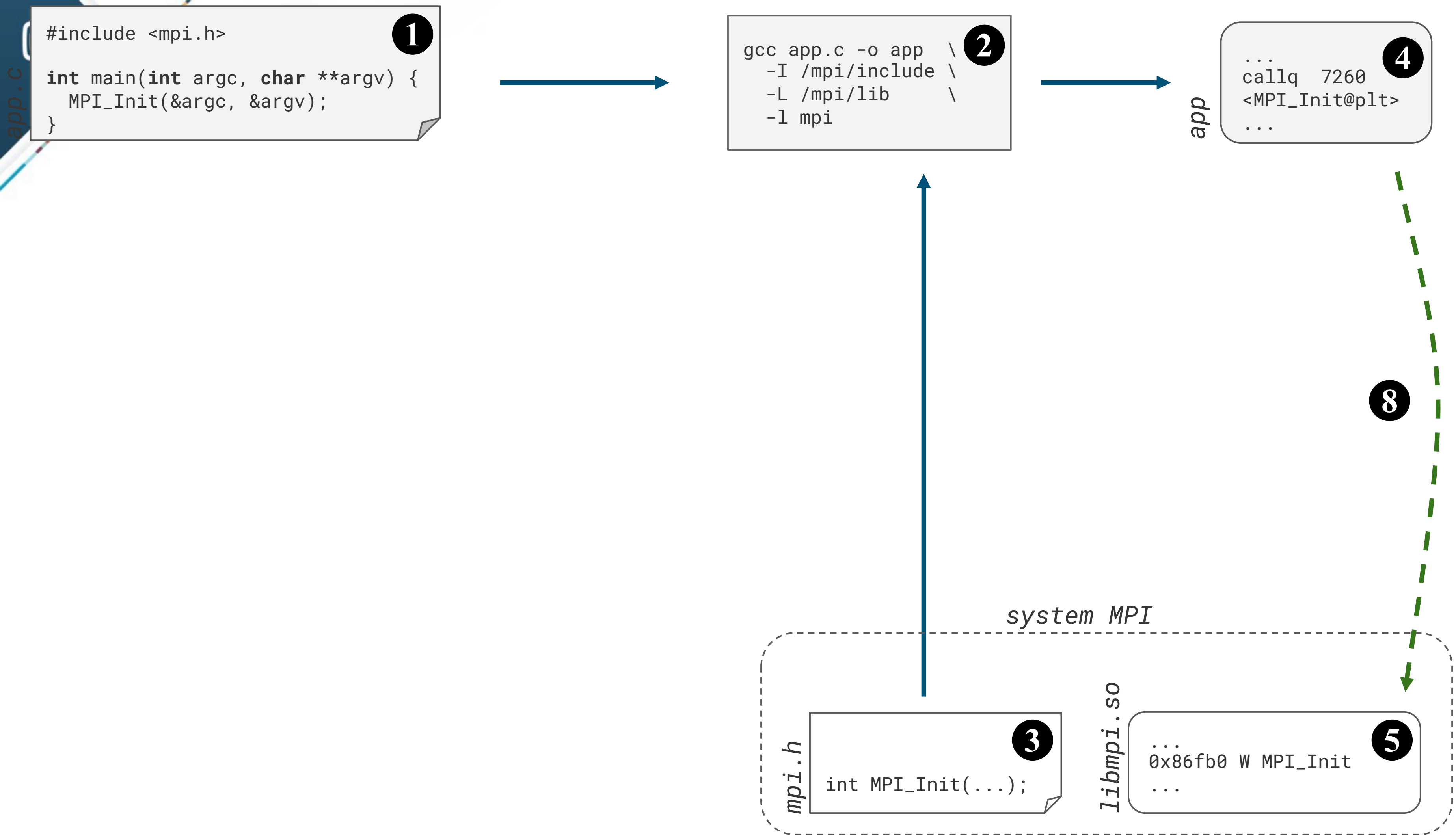
A Practical Challenge: Deploying MPI experiments on a Supercomputer

- Large-scale systems are tightly controlled
    - Can’t just make whatever changes you want
- Usually one MPI (or maybe two) are deployed on the system
    - Rarely bugfixed (if ever)
    - Even more rarely are new features added
- Difficult or impossible to make experimental modifications

- MPI has a well-defined standard
    - Take advantage of this + how OS loads libraries to inject modifications

TEMPI’s Architecture: Interposer Library





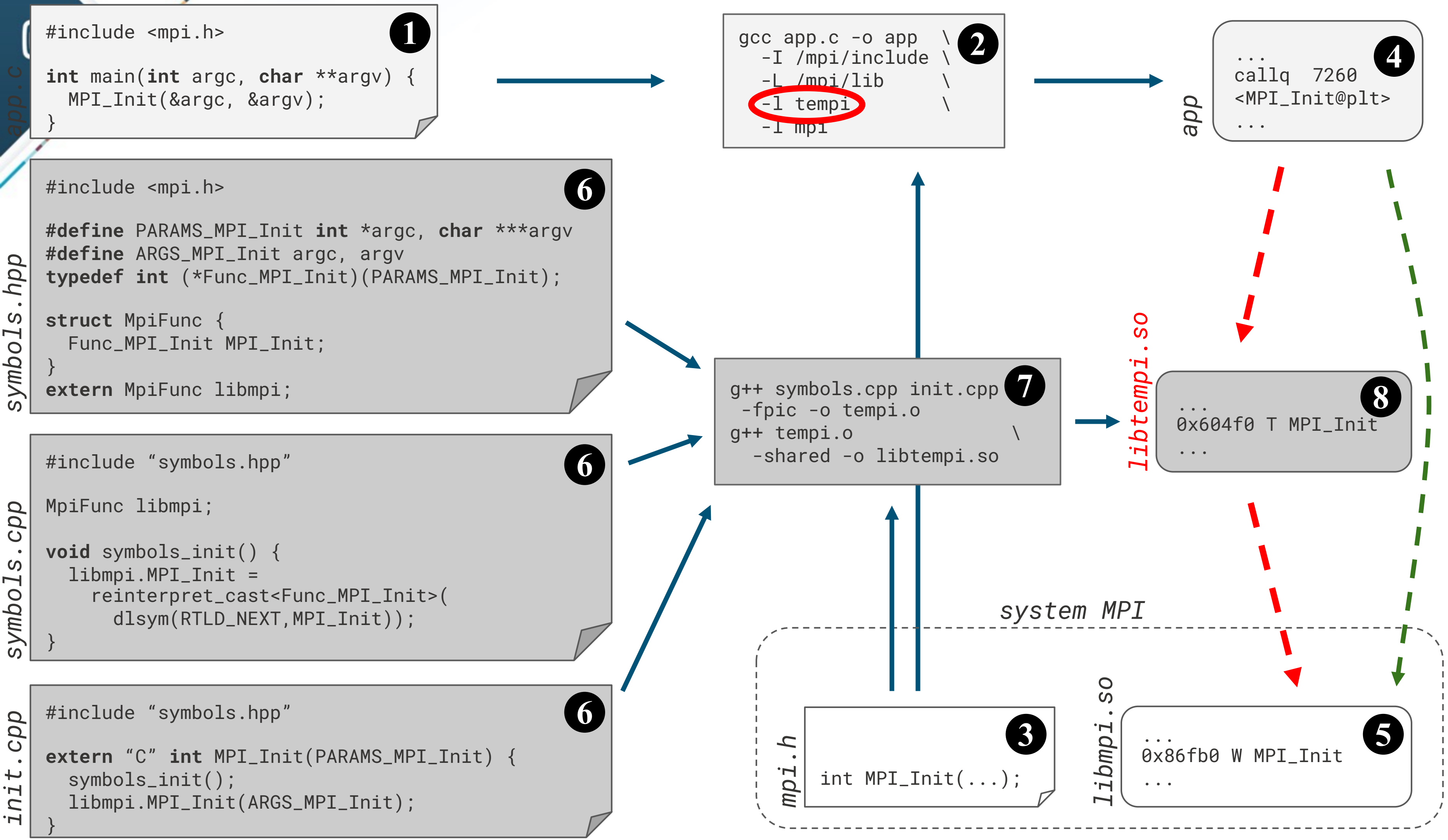
```
#include <mpi.h>

int main(int argc, char **argv) {
  MPI_Init(&argc, &argv);
}
```

```
gcc app.c -o app   \
  -I /mpi/include \
  -L /mpi/lib     \
  -l mpi
```

```
...
callq  7260
<MPI_Init@plt>
...
```

```
int MPI_Init(...);
```

```
...
0x86fb0 W MPI_Init
...
```



app.c

```
#include <mpi.h>

int main(int argc, char **argv) {
  MPI_Init(&argc, &argv);
}
```

```
gcc app.c -o app   \
  -I /mpi/include \
  -L /mpi/lib     \
  -l tempi        \
  -l mpi
```

app

```
...
callq  7260
<MPI_Init@plt>
...
```

symbols.hpp

```
#include <mpi.h>

#define PARAMS_MPI_Init int *argc, char ***argv
#define ARGS_MPI_Init argc, argv
typedef int (*Func_MPI_Init)(PARAMS_MPI_Init);

struct MpiFunc {
  Func_MPI_Init MPI_Init;
}
extern MpiFunc libmpi;
```

symbols.cpp

```
#include "symbols.hpp"

MpiFunc libmpi;

void symbols_init() {
  libmpi.MPI_Init =
    reinterpret_cast<Func_MPI_Init>(
      dlsym(RTLD_NEXT,MPI_Init));
}
```

init.cpp

```
#include "symbols.hpp"

extern "C" int MPI_Init(PARAMS_MPI_Init) {
  symbols_init();
  libmpi.MPI_Init(ARGS_MPI_Init);
}
```

```
g++ symbols.cpp init.cpp
 -fpic -o tempi.o
g++ tempi.o                 \
  -shared -o libtempi.so
```

libtempi.so

```
...
0x604f0 T MPI_Init
...
```

mpi.h

```
int MPI_Init(...);
```

libmpi.so

```
...
0x86fb0 W MPI_Init
...
```

Conclusions & Future Work

- Canonicalization approach works
  - 👍 Speedup for unmodified applications on OLCF summit
  - 👍 Any strided datatype
- Simple performance model to select GPU data transfer method
  - 👍 speedup
  - 👎 < 2x speedup
- Interposed library approach nice for experiments & prototype deployment
  - 👍 Easy to use without system privileges
  - 👎 Limited integration with existing MPI
- OpenMPI, MPICH, MVAPICH have other strategies
  - Use if available - covers some or all of the same problems
  - Comparison of MPI datatype performance would be useful to community
- github.com/cwpearson/tempi

Acknowledgements

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Thank you

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github.com/cwpearson/tempi

This work was completed prior to joining Sandia National Labs.