An MPI Halo-Cell Implementation for Zero-Copy Abstraction

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Introduction (1/3)

HPC machines are rapidly shifting to higher concurrency

- Now gathering millions of cores
- Intra-node parallelism is rapidly increasing (several hundred threads) (Xeon Phi / KNL)
- This with a smaller memory per thread

It is well aknowledged that applications will have to evolve in order to take advantage of such architectures MPI + X being often refered to as a potential solution.

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Introduction (2/3)

But what does it mean…

- What is this **X** ?

Distributed Memory	Shared-Memory	Accelerators	Logical Address Spaces
MPI and optimized intra-node communications	OpenMP Cilk, TBB Pthreads, …	GPUs, FPGAs	PGAS, DSM

There are several alternatives:
MPI + OpenMP, MPI + GPU, MPI + PGAS, ….

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Introduction (3/3)

But what does it mean…

- Why MPI is not sufficient ? Why do we need this X ?

In our paper, we propose to model this limitation when considering domain-splitting in distributed memory context

We show that distributed memory poses problems of:

- Memory due to domain replication
- Communication overhead and therefore scalability

Then, we propose an MPI level abstraction solving these issues for domain splitting by providing the advantages of shared-memory programming.

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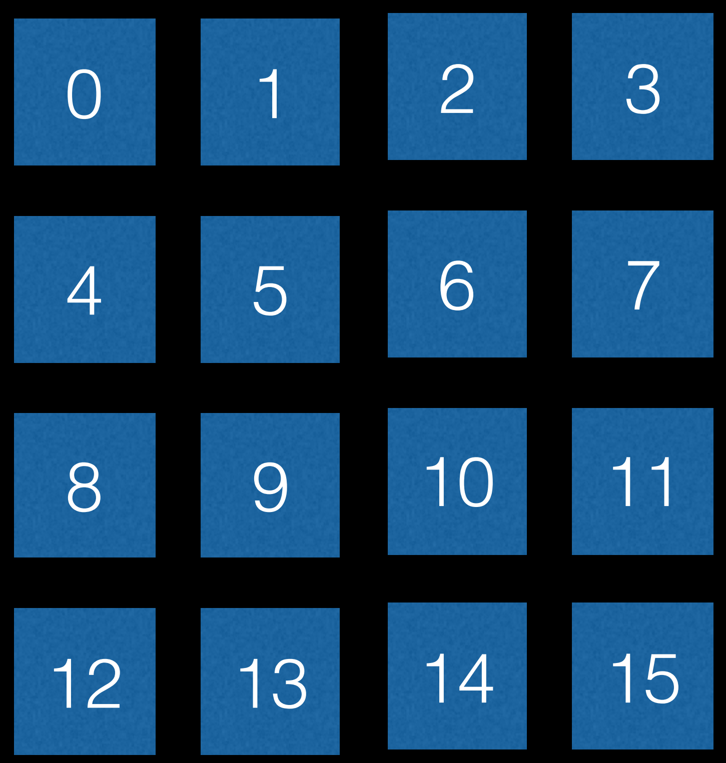
Domain Splitting (1/2)



We consider the case where computation is done over a distributed domain (often as a stencil) creating dependencies between cells structured as a mesh

—> **This covers a wide range of applications (not all)**

Domain Splitting (2/2)

It is common knowledge for all MPI programmers that such domain spitting requires halo/ghost cells on local domain boundaries.

Is it possible to provide a simple model of the halo-cells ? What is the performance impact for common topologies ?

Yes (first part of our paper)

Domain Splitting on four processes

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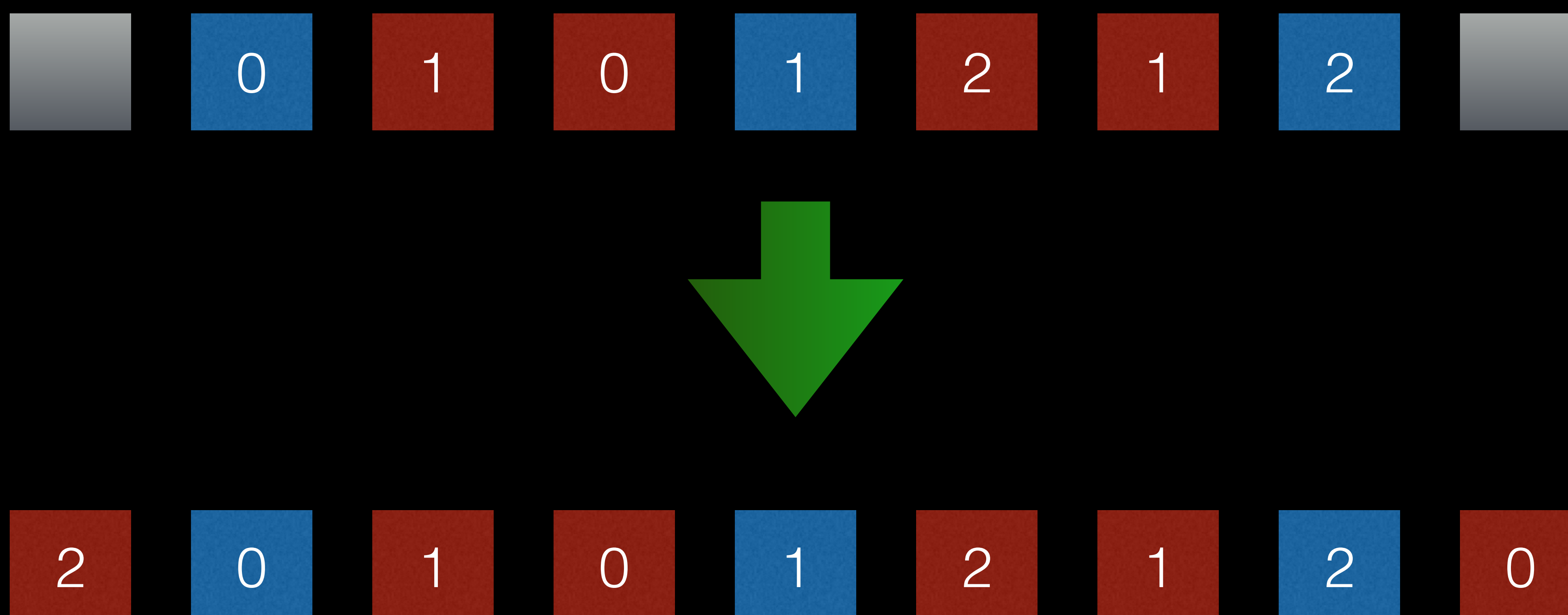
Halo-Cell Model (1/6)

To derive this model, we considered wrapped-around meshes (tori) instead of regular ones in order to have a regular mesh layout (no border effect).



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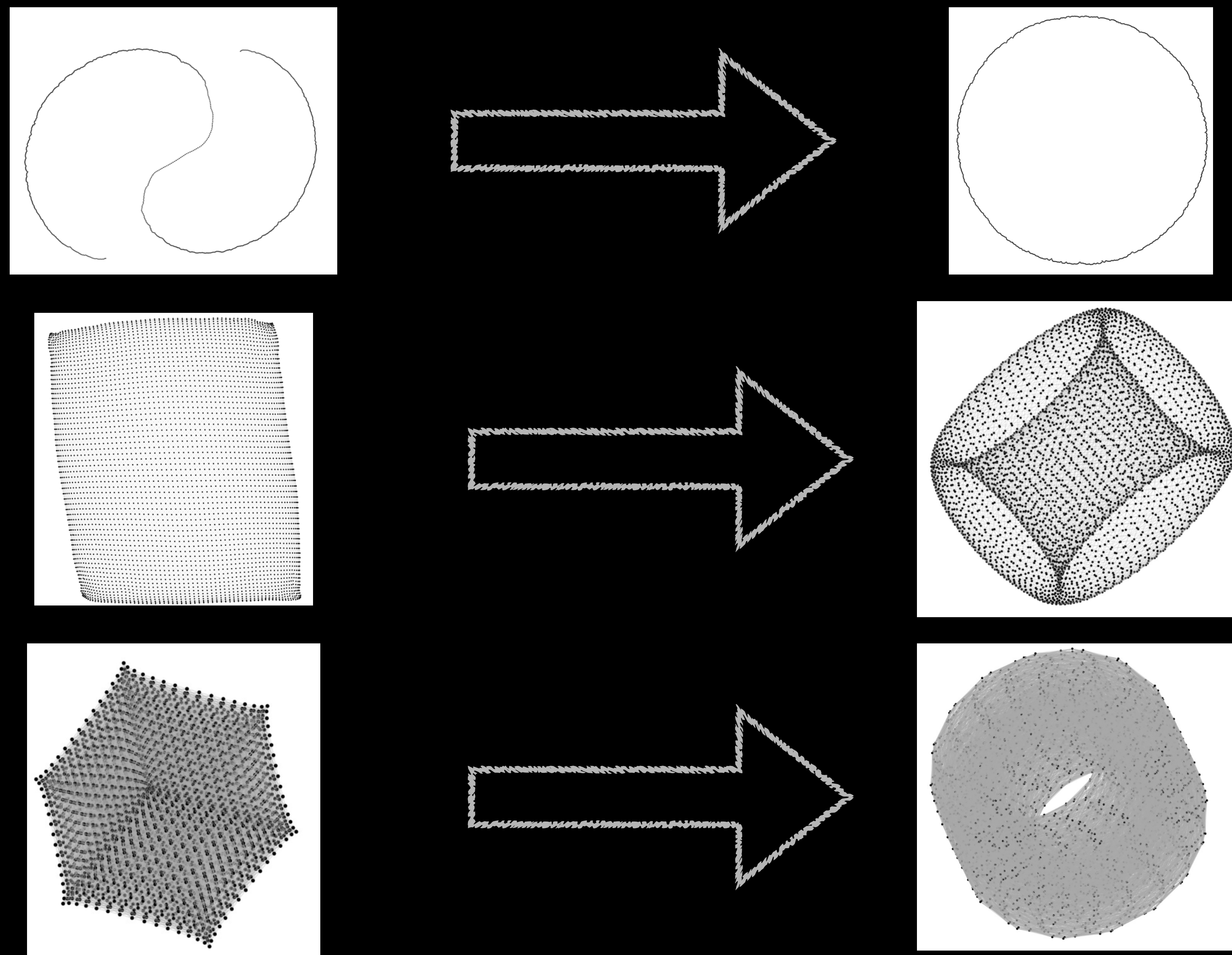
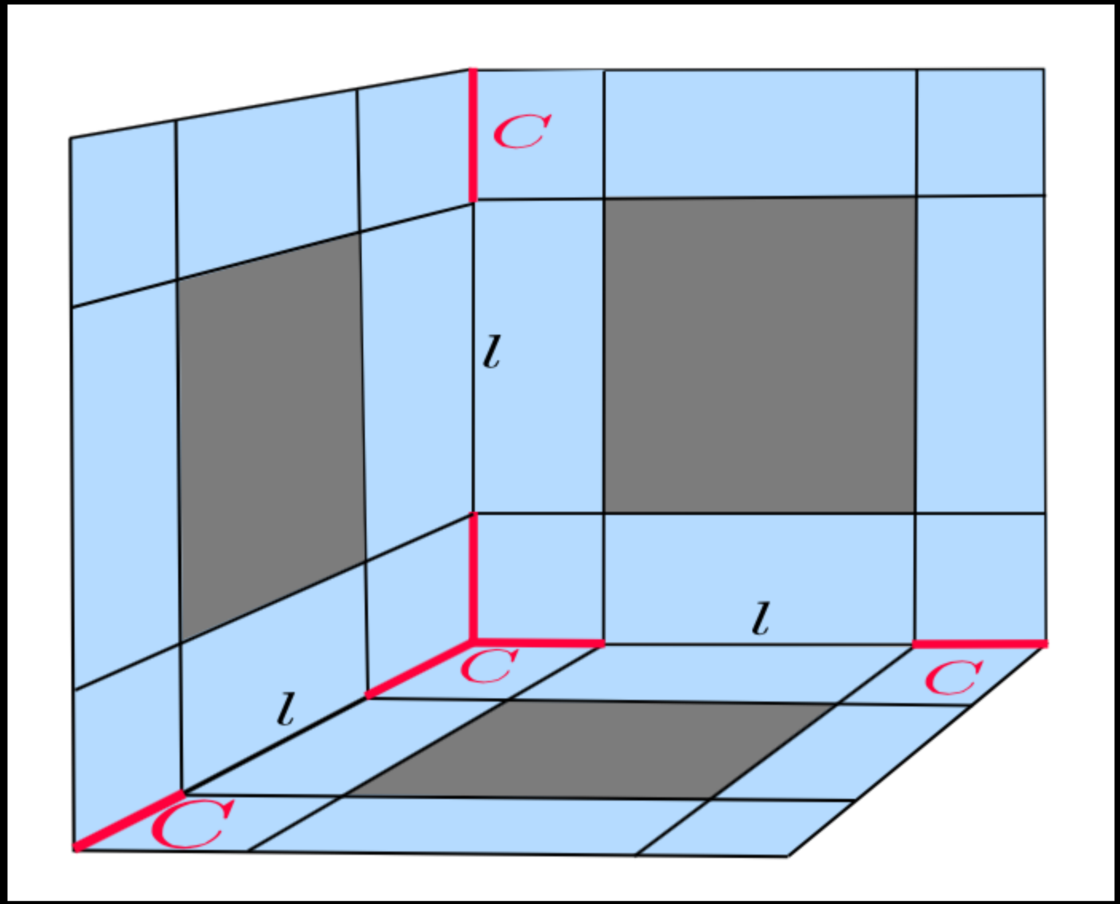
Halo-Cell Model (2/6)



These regular topologies are nonetheless completely representative of unwrapped ones dealing with the level of connectivity between distributed areas.

Halo-Cell Model (3/6)

n: Number of cells
C: Number of halo layers
d: Mesh dimension
l: Characteristic length of the topology



$$l(n,d) = n^{\frac{1}{d}}$$

$$N_g(n,d) = (l(n,d) + 2C)^d - l(n,d)^d = (n^{\frac{1}{d}} + 2C)^d - n$$

« Subtract a mesh without halo-cells to a mesh with a characteristic length increased of 2C. »

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Halo-Cell Model (4/6)

d	1	2	3
$N_g(p, n, C)$	$2pC$	$4pC(\sqrt{\frac{n}{p}} + C)$	$2pC(3\frac{n}{p}^{\frac{2}{3}} + 6C\frac{n}{p}^{\frac{1}{3}} + 4C^2)$

2 * 3 (processes) * 1 (layer) = 6 halo cells

Halo-Cell Model (5/6)

2D

$$4pC\left(\sqrt{\frac{n}{p}}+C\right)$$

= 4.4.1(sqrt(16 / 4) + 1)

= 4.4.1(sqrt(4) + 1)

= 4.4.3

= 48 = (4 * 12) halo cells

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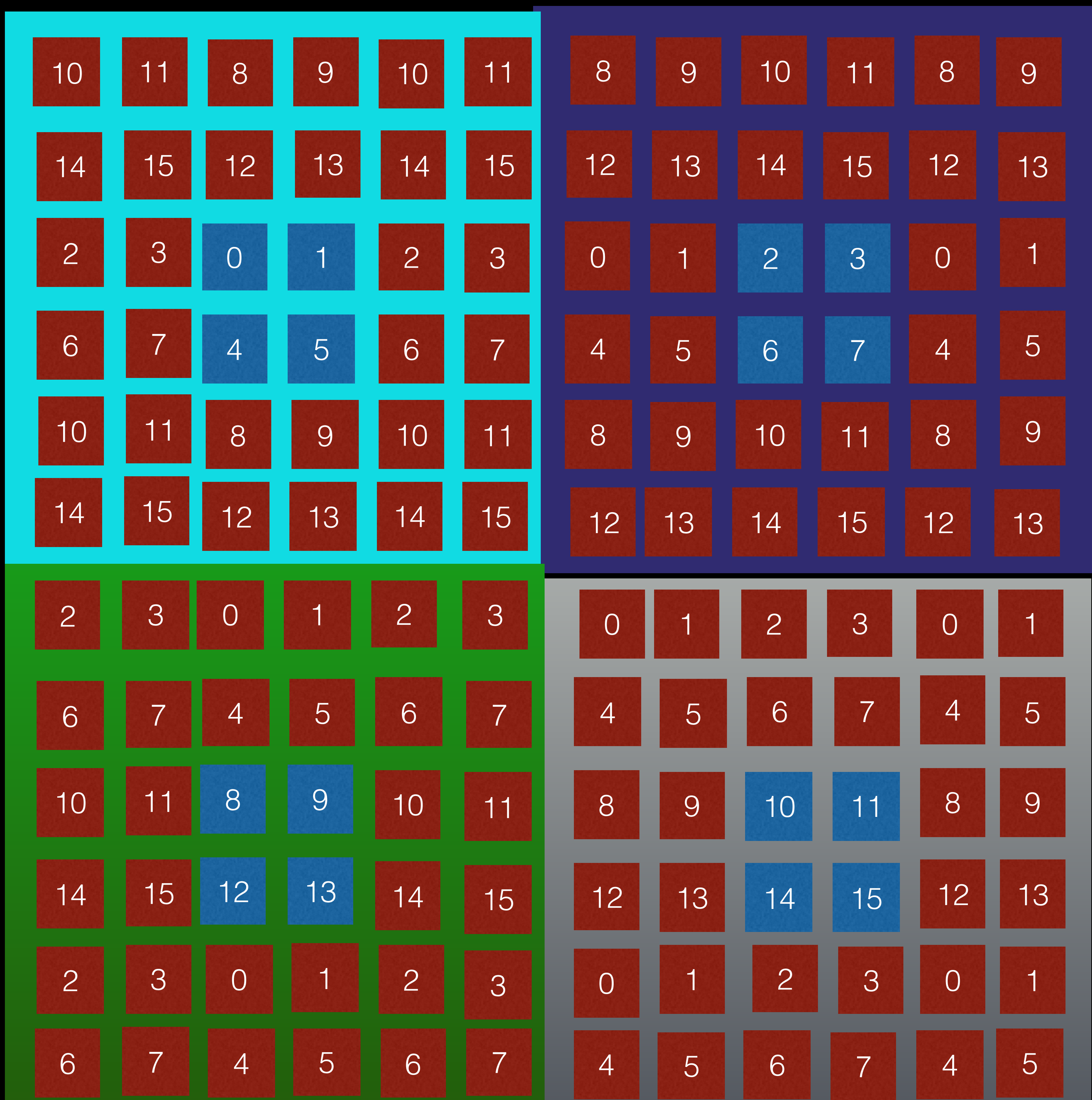
Halo-Cell Model (6/6)



2D (two layers)

$$4pC\left(\sqrt{\frac{n}{p}} + C\right)$$

= 4.4.2(sqrt(16 / 4) + 2)

= 4.4.2(sqrt(4) + 2)

= 4.4.2.4

= 128 = (4 * 32) halo cells

Halo-Cells and Performance (1/4)

$$S(n, p) = \frac{s(n)}{\frac{s(n)}{p} + comm(n, p)}$$

Starting from the well-known speedup equation, it can be seen that strong-scaling speedup is bounded by communications which are directly linked to the number of halo-cells.

—> Computation time should be much larger than communication time. There should be more local cells than halo cells with a complex computation. **However, this ratio changes with *p* (strong scaling)**

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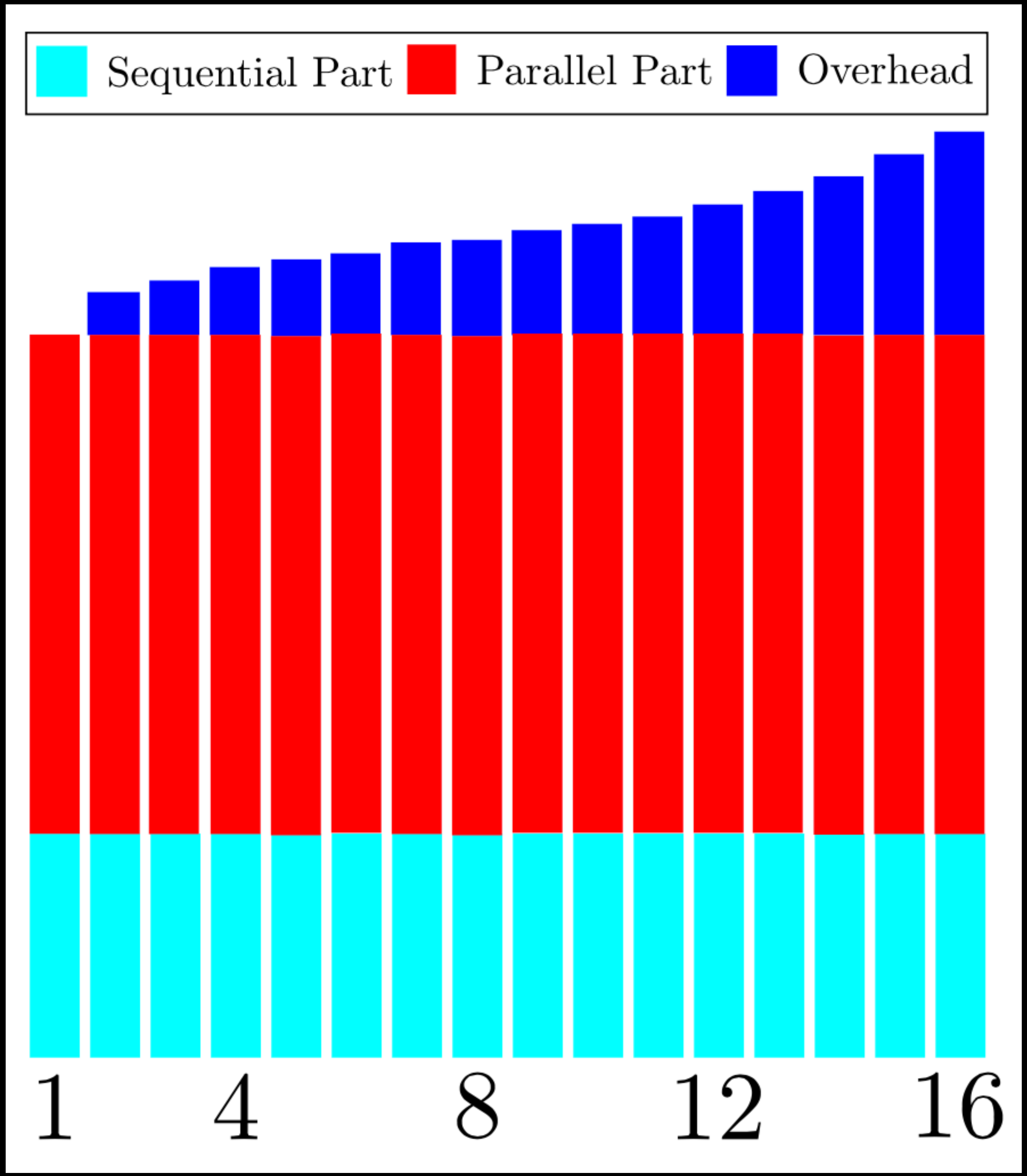
Halo-Cells and Performance (2/4)

If we now consider the weak-scaling model, we have n/p which is a constant as is the ghost cell ratio.

Communication cost has then to be independent of the number of processes, in order to allow weak-scaling. Which is true for regular decomposition?



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Halo-Cells and Performance (3/4)

	1D	2D	3D
$n(r,p,C)$	$\frac{2pC}{r}$	$\frac{4pC^2}{r^2}(r+2+2\sqrt{1+r})$	$\frac{2pC^3}{r^3}(r^2+3r(1+r)^{\frac{2}{3}}+6r(1+r)^{\frac{1}{3}}$ $+9[r+1+(1+r)^{\frac{2}{3}}+(1+r)^{\frac{1}{3}}])$
$n(1\%,p,1)$	$200p$	1.61×10^5p	2.18×10^8p
$n(1\%,p,2)$	$400p$	6.43×10^5p	1.74×10^9p
$n(1\%,p,3)$	$600p$	1.44×10^6p	5.89×10^9p
$n(10\%,p,1)$	$20p$	$1679p$	2.37×10^5p
$n(10\%,p,2)$	$40p$	$6716p$	1.90×10^6p
$n(10\%,p,3)$	$60p$	$15111p$	6.42×10^6p
$n(50\%,p,1)$	$4p$	$79p$	$2639p$
$n(50\%,p,2)$	$8p$	$317p$	$21177p$
$n(50\%,p,3)$	$16p$	$712p$	$71272p$

When doing weak-scaling, it is desirable to limit the ghost-cell ratio in order to completely hide communication costs.

However, memory per thread is decreasing:

In 3D, if you want 1% of ghost cells with one layer, you need 1.64 GB of memory (for 8 bytes cells). Compare it to the 34 MB / Thread on a Xeon Phi.

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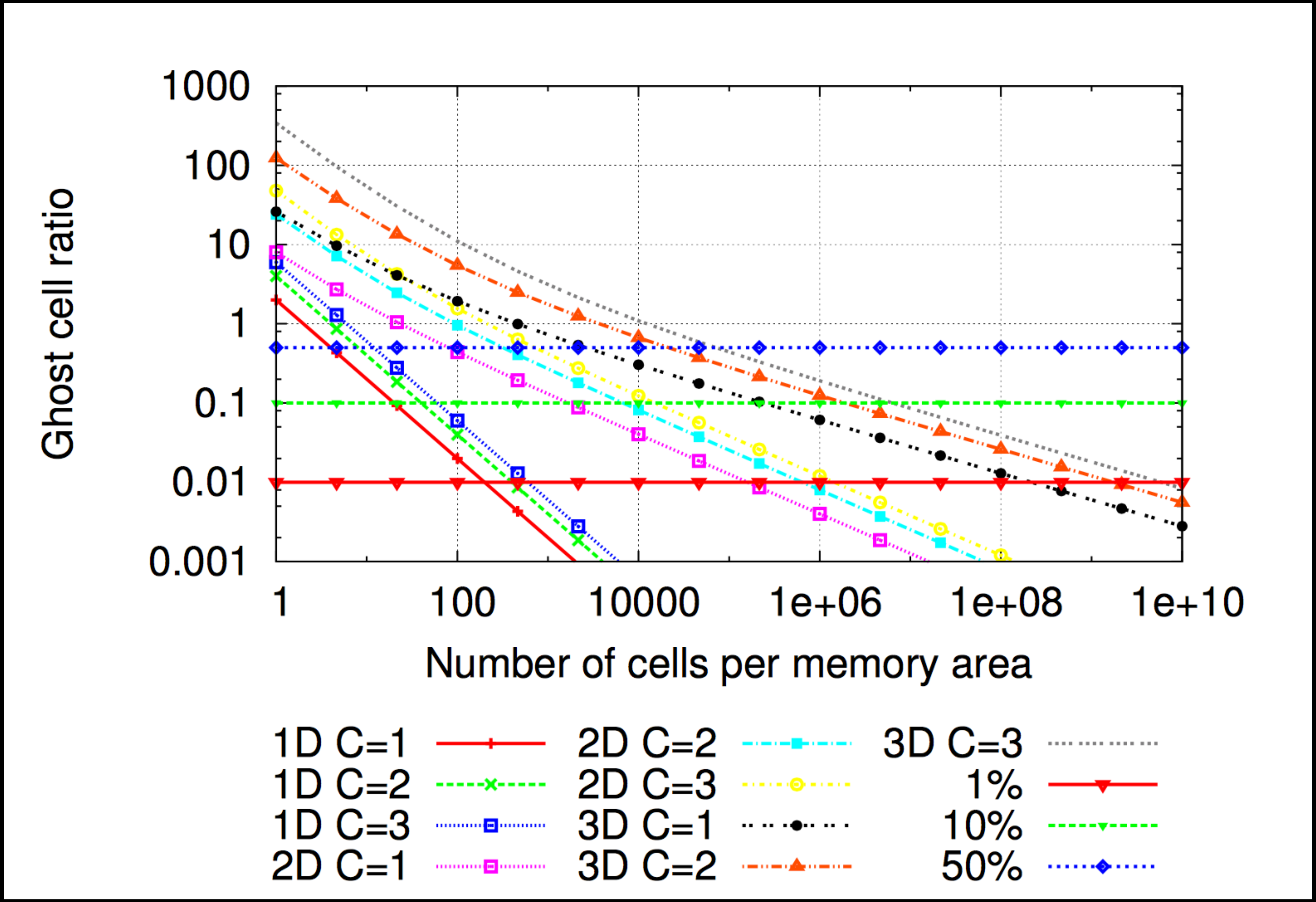
Halo-Cells and Performance (4/4)



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Hybrid Approach

Intra-node parallelism is then a direct way of reducing the ghost cell ratio and then improving scalability by overcoming the per thread memory limitation.

- Reducing communication cost
- Limiting ghost-cell memory overhead while freeing memory for computation (hiding comms)

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MPI Optimized Intra-Node Messaging

A lot of work has been done to optimize intra-node communications:

- SHM memory segments
- KNEM kernel module
- Or since Linux 3.2 Cross Memory Attach (CMA)
- Direct copy in thread-based MPI
- It is even possible to use the HCA to emit RDMA

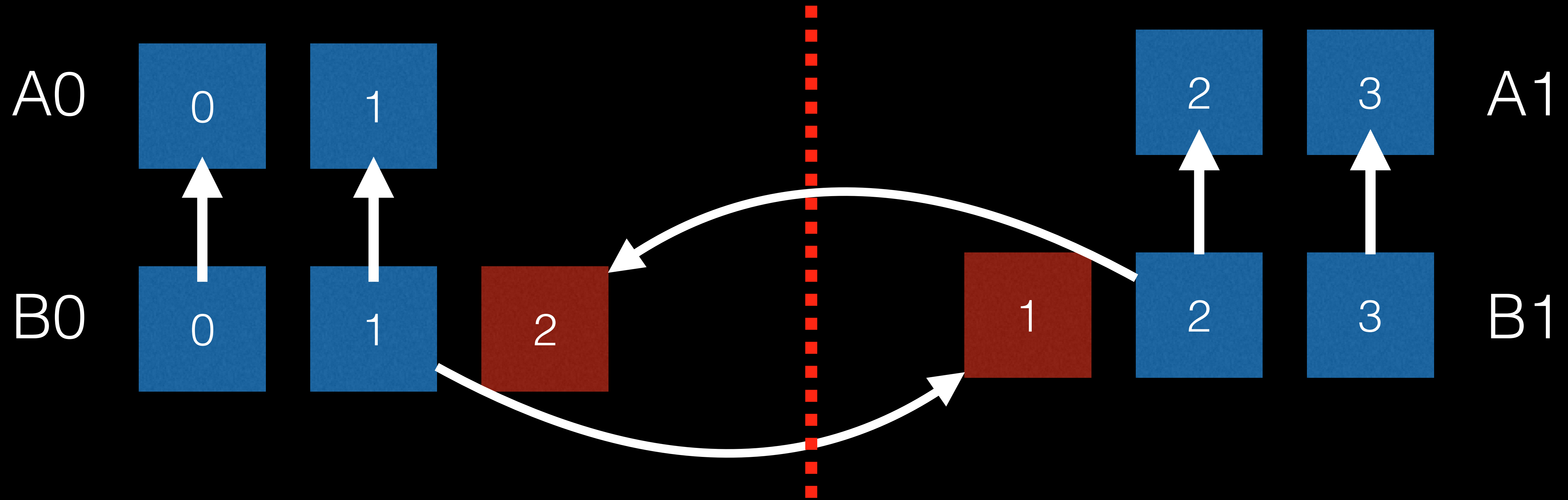
Such approaches efficiently reduce node-local communication cost but do not reduce/remove the memory associated with halo cells which still has to be duplicated.

MPI Halo

We propose a Halo Cell abstraction providing the advantages of shared-memory models while remaining close to MPI semantics:

- Transparent use of larger memory areas
- Removal of memory duplications between tasks on the same node
- Removal of node-local communications (no copies — Zero copy)
- Support for computation outside of node boundaries (no mixing)

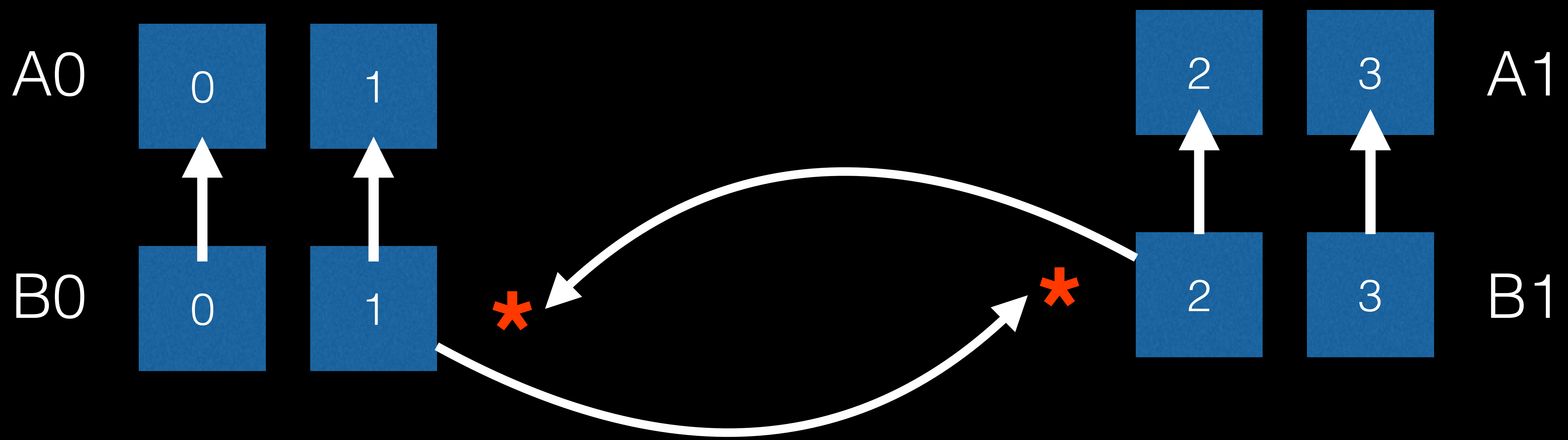
MPI Halo Principle (1/4)



Classical Ghost Cell Approach With Copies

When doing a stencil, most applications use two meshes, one for « t » and another for « t+1 », approach required due to the spatial-dependency between cells.

MPI Halo Principle (2/4)



What if local cells (located on the same node) could be resolved as local pointers — no copies would be required.

The source mesh being accessed in read-only is not necessary to duplicate data.

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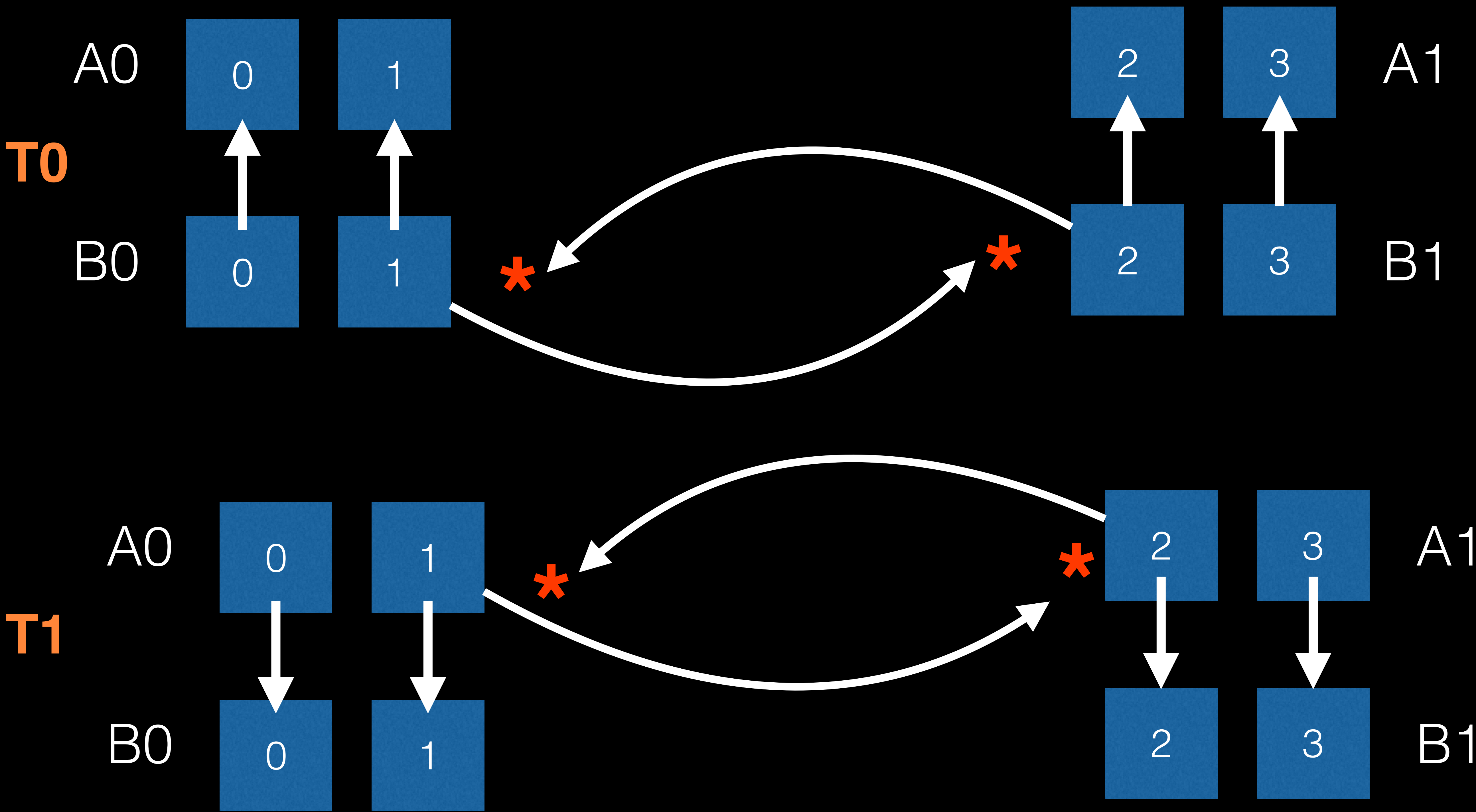
MPI Halo Principle (3/4)



Pointer exchanges allow mesh-switching

MPI Halo Principle (4/4)

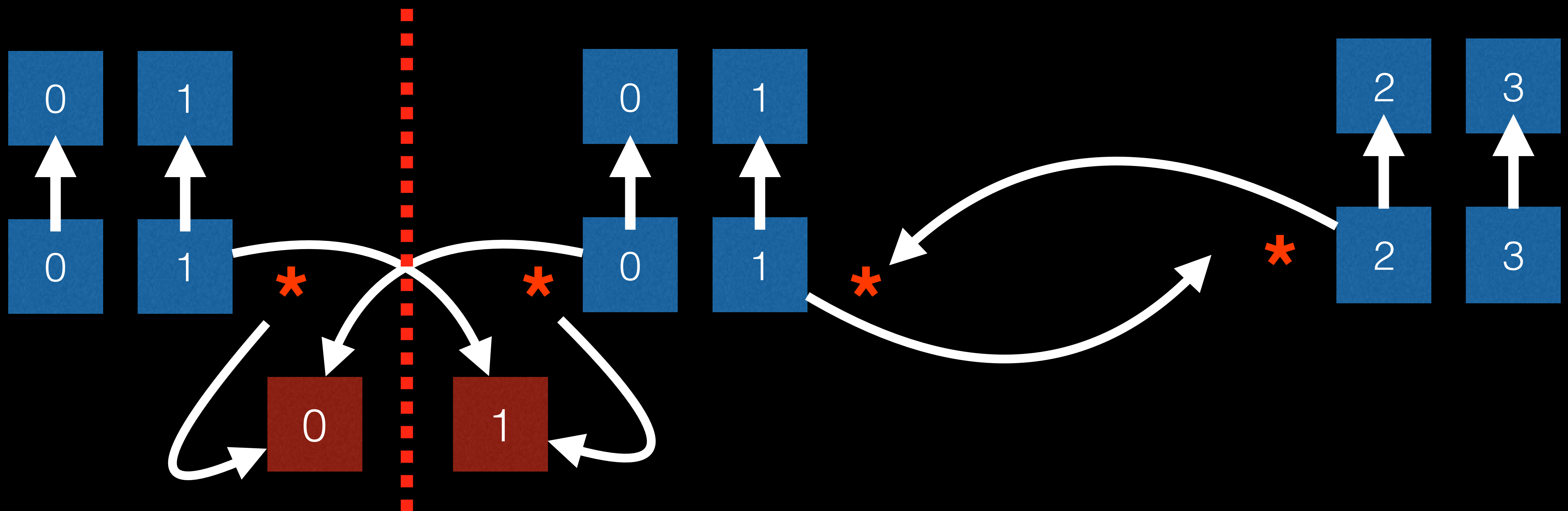


Illustration of both inter-node and intra-node exchanges with MPI-Halo cells.

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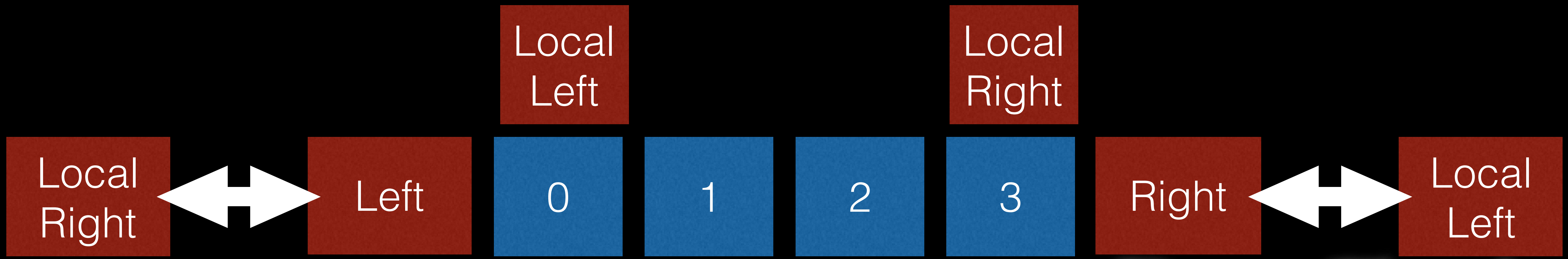
MPI Halo Example (1D splitting) (1/2)

```
/*----- Initialization (Done once) */
MPI_Halo local_left, local_right, left, right;
/* Name Cells and provide Layout */
MPIX_Halo_cell_init(  &local_left, "Local Left" , MPI_INT, 1024 );
MPIX_Halo_cell_init(  &local_right, "Local Right" , MPI_INT, 1024 );
MPIX_Halo_cell_init(  &left, "Remote Right" , MPI_INT, 1024 );
MPIX_Halo_cell_init(  &right, "Remote Left" , MPI_INT, 1024 );
/* Bind Cells */
MPI_Halo_ex ex;
MPIX_Halo_exchange_init( &ex );
MPIX_Halo_cell_bind_local( ex, local_left );
MPIX_Halo_cell_bind_local( ex, local_right );
MPIX_Halo_cell_bind_remote( ex, right, right_process,  "Local Left" );
MPIX_Halo_cell_bind_remote( ex, left, left_process,  "Local Right" );
/* Generate Communications */
MPIX_Halo_exchange_commit( ex );
```



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MPI Halo Example (1D splitting) (2/2)

```c
/*----- Compute Loop (Called at each time-step)*/
while( compute )
{
  /* Register local cell data */
  MPIX_Halo_cell_set( local_left, mesh  );
  MPIX_Halo_cell_set( local_right, right_coll( mesh )  );
  /* Start asynchronous communications */
  MPIX_Halo_iexchange( ex );
  /* ... Compute mesh center ... */
  MPIX_Halo_iexchange_wait( ex );
  /* Retrieve Ghost arrays */
  int * left_ghost, * right_ghost;
  MPIX_Halo_cell_get( left,  (void **)&left_ghost );
  MPIX_Halo_cell_get( right, (void **)&right_ghost );
  /* ... Compute mesh boundaries ... */
  /* Swap Meshes */
  Mesh * tmp = mesh;
  mesh = oldmesh;
  oldmesh = tmp;
}
```

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MPI Halo Interface

MPI_Halo:

- Automatic buffer abstraction (local or remote)
- Can be set to a value when local
- A pointer can be retrieved when remote
- Supports MPI data-types (packing abstraction)

MPI_Halo_ex:

- Build the communication scheme between MPI_Halo
- Buffers are named (no abstract offsets)
- An error is reported if the remote is not present
- No offset is passed to communication calls
  - ➡ **Boundaries have to be handled as particular case**
- Copy can still be forced when the remote is modified

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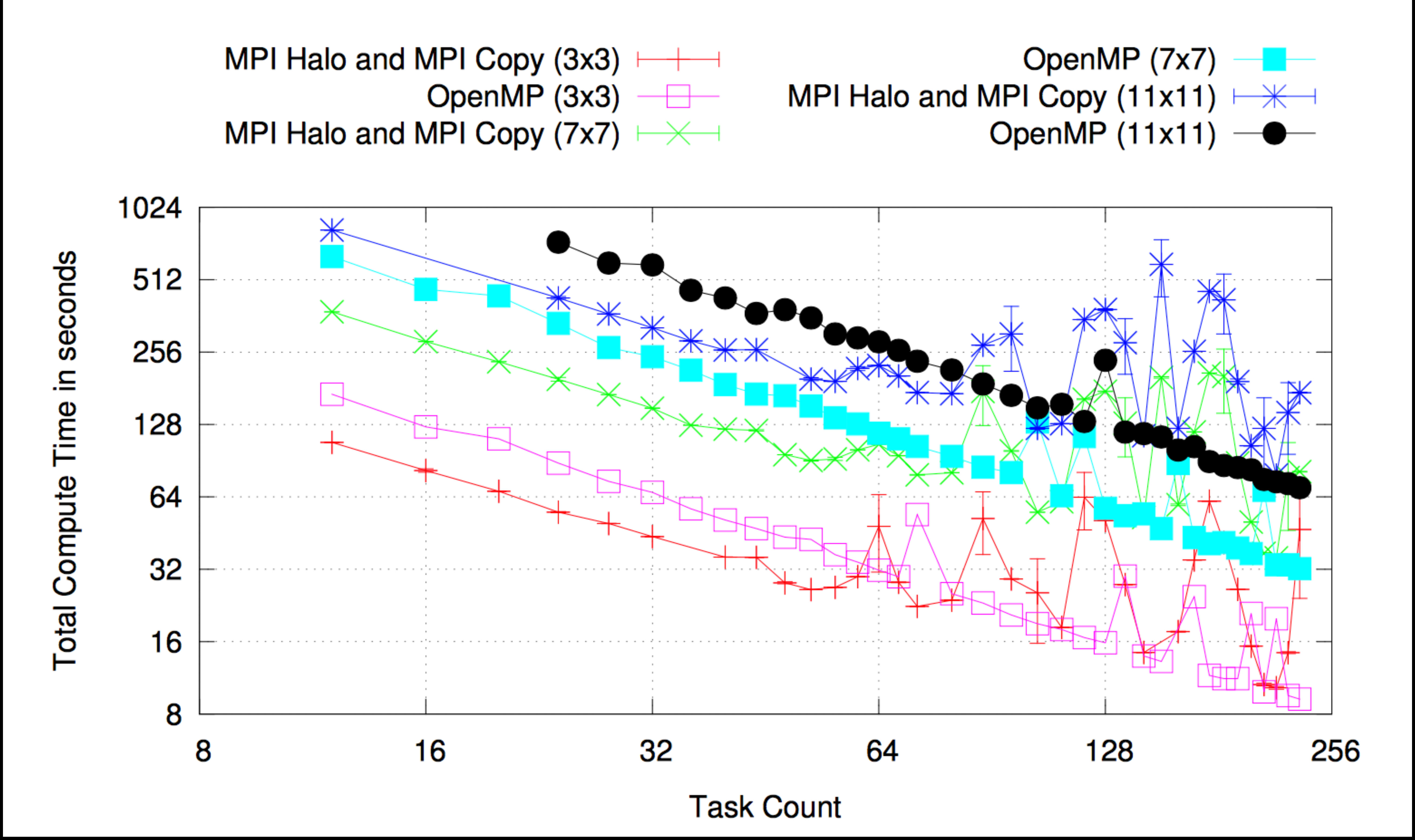
MPI Halo Performance Results (1/3)

Our test-case was the convolution of a 5616x3744 RBG image implemented in OpenMP, MPI-Halo, also forcing buffer allocation to behave like the classical ghost-cell approach. We tested this benchmark with various convolution kernel sizes.

Our MPI-Halo interface has been implemented in the MPC runtime which is a thread-based MPI, making node-level exchanges trivial (shared-memory). Nothing prevents the MPI Halo model to be ported to process-based MPI supposing a previous memory registration.

MPI Halo Performance Results (2/3)



Computation Time

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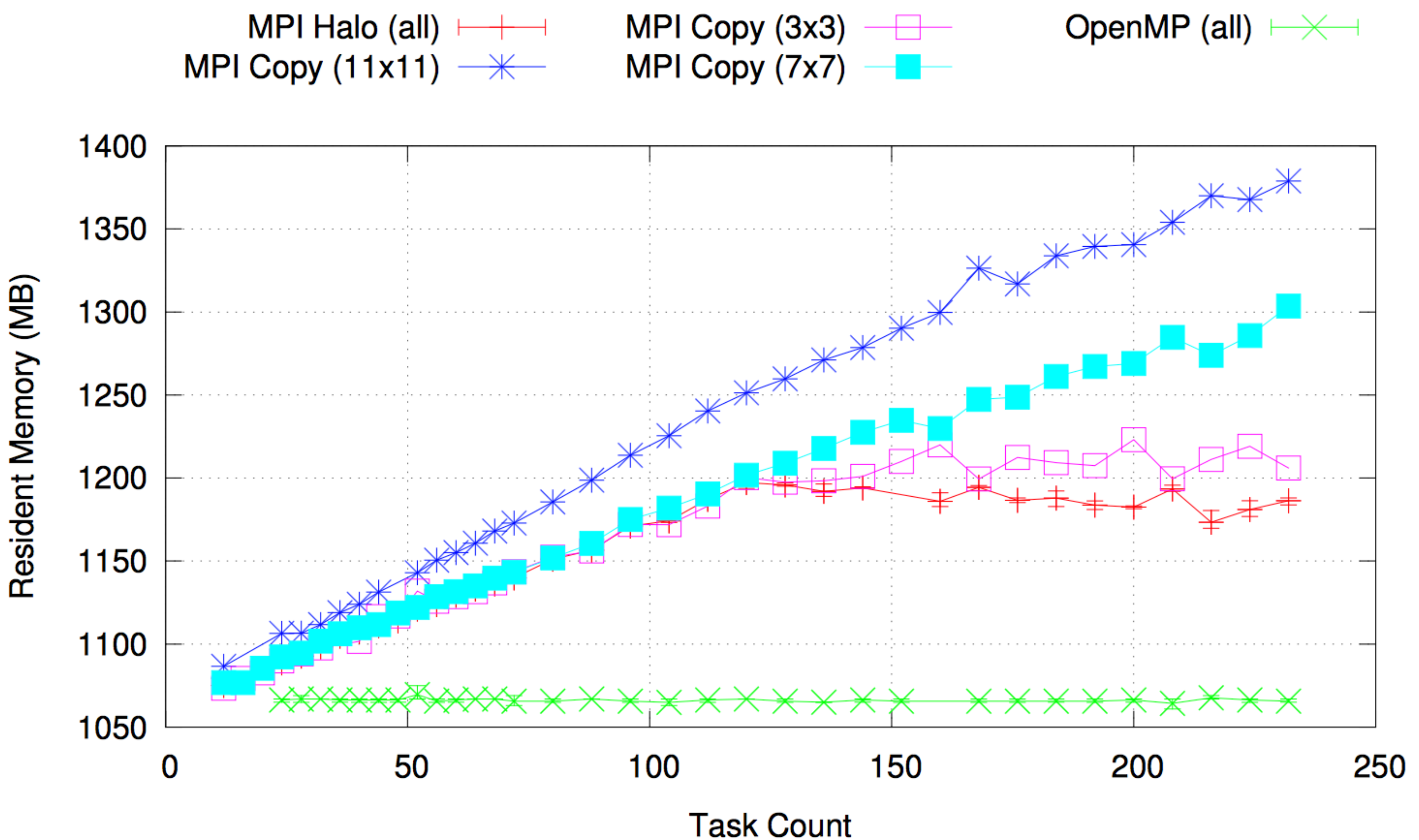
MPI Halo Performance Results (3/3)



(b) Memory Usage (Resident)

Memory Usage

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Conclusion

Halo-Cell Model:

- Introduced a model of the halo-cell ratio
- Explained that scaling was highly impacted by this ratio
- Shown that distributed memory was hitting the per-thread memory barrier, encouraging hybrid models to achieve better ghost-cell ratios particularly for higher dimensions (3D with several layers).

MPI_Halo:

- Proposed an MPI based solution to the domain decomposition issue we exposed (buffer aliasing)
- Allows a clear definition of a communication scheme with static validation of buffer matching (size, name)
- Consistent with inter-node parallelism (unlike OpenMP)

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An MPI Halo-Cell Implementation for Zero-Copy Abstraction

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