Heterogeneous Computing for Scientific Applications

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Outline

- Analysis, parallelism characterization of NAS-MZ suite of benchmarks
- NPB-MZ Hybrid Design and Implementation
- Work distribution schemes for hybrid executions
- Evaluation Results

NPB-MZ Parallel Benchmarks

- Data Structures and Input Size
- Computation Structure
- Sources of Parallelism

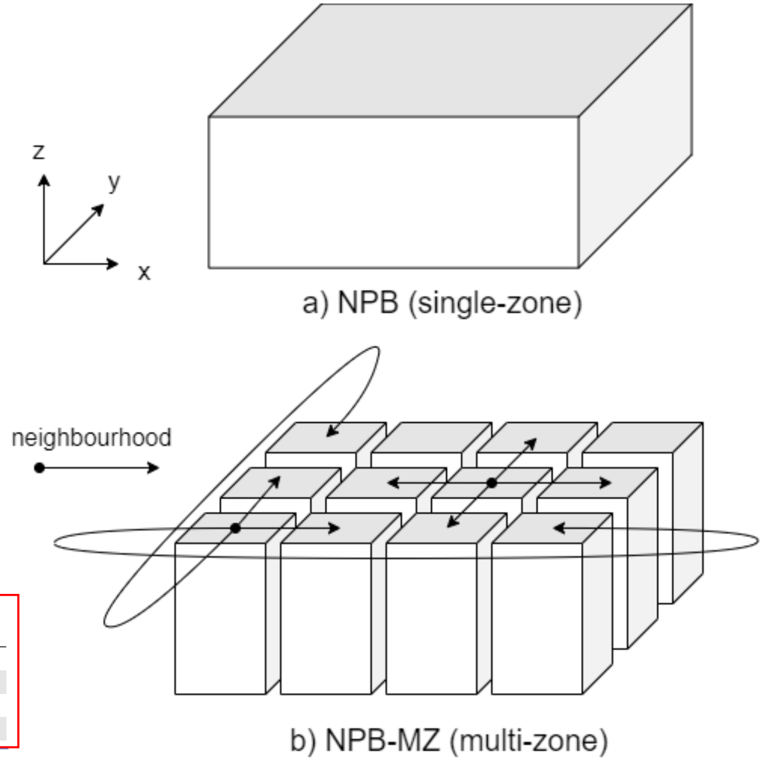
Data Structures and Input Size

- Data Structures
  - 3D mesh organized in “zones”
    - A zone is a set of multidimensional matrices
- Input Size

  size increases

  - Different classes: A, B, C, D, E
  - Number of zones: from 16 to 4096
- Iterative solvers
  - From 250 to 500 iterations

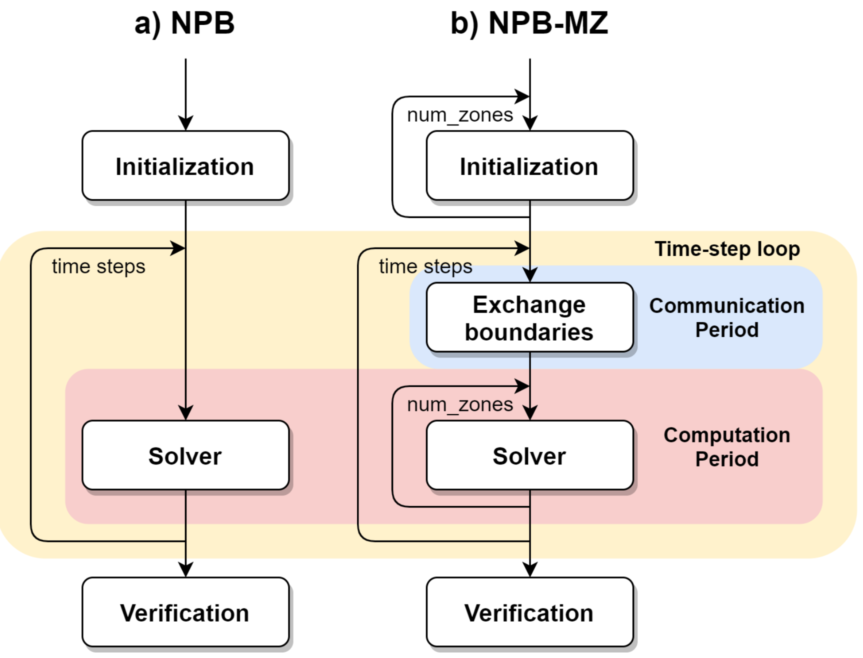
Input Class	3D volume x × y × z (points)	Memory (GB)	Num. zones (x × y) LU	Num. zones (x × y) SP & BT	Zone size (points per zone) LU	Zone size SP	Zone size BT	Time steps LU	Time steps SP	Time steps BT
B	304 × 208 × 17	≈ 0.2	4 × 4	8 × 8	67 184	16 786	from 2 992 to 59 976	250	400	200
C	480 × 320 × 28	≈ 0.8	4 × 4	16 × 16	268 800	16 800	from 2 912 to 60 648	250	400	200
D	1 632 × 1 216 × 34	≈ 13	4 × 4	32 × 32	4 217 088	65 892	from 11 968 to 243 236	300	500	250
E	4 224 × 3 456 × 92	≈ 250	4 × 4	64 × 64	83 939 328	327 888	from 59 248 to 1 203 452	300	500	250



a) NPB (single-zone)
b) NPB-MZ (multi-zone)

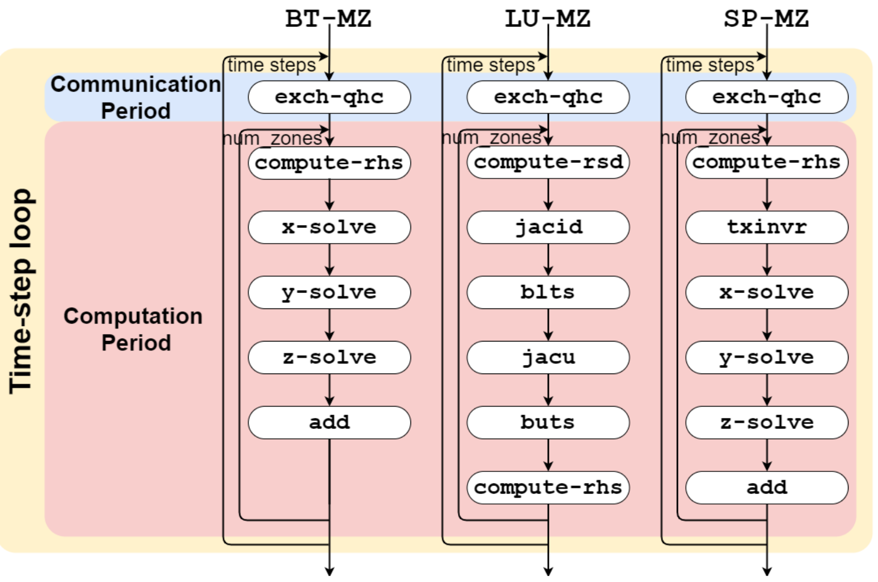
Computational Periods

- For all benchmarks:
  - Initialization
    - Several stages
  - Computation Period
    - Solver composed of several stages
    - Applied to each zone
  - Communication Period
    - Exchange of border values between zones
    - One single stage
  - Verification



Stages within the Compute Period and Communication Period

- Three benchmarks:
  - BT-MZ
    - “Many zones with small, medium and large sizes”
  - SP-MZ
    - “Many zones with small sizes and all of them equal”
  - LU-MZ
    - “Few zones and with very large size”
  - Computation Period
    - Composed of different stages per each benchmark
  - Communication Period
    - Single stage and common to each benchmark



Computation Period(I): Inter-Zone Parallelism

- Traversal of zones
  - Single loop that runs over the set of zones
  - Zones are identified
    - Number from 0 up to the NUM-ZONES-1
  - Several stages applied per each zone
    - Different in BT-MZ, SP-MZ and LU-MZ

- Example with SP-MZ:

```
for (t=0; t<ITERS; t++) {

  exch-qbc();

  for (zone = 0; zone < NUM-ZONES; zone++) {

    compute-rhs(zone, ...);
    txinvr(zone, ...);
    x-zolve(zone, ...);
    y-solve(zone, ...);
    z-solve(zone, ...);
    add(zone, ...);
  }
}
```

Inter-zone parallelism

Computation Period(II): Intra-Zone Parallelism

- Processing of one stage on one zone
  - Sequence of several loop nests
  - For CPU execution
    - Loop nest is parallelized (e.g.: OpenMP)
  - For GPU execution
    - Loop nest is transformed to CUDA kernel

- Example: BT-MZ, `x-solve` stage

Intra-zone parallelism

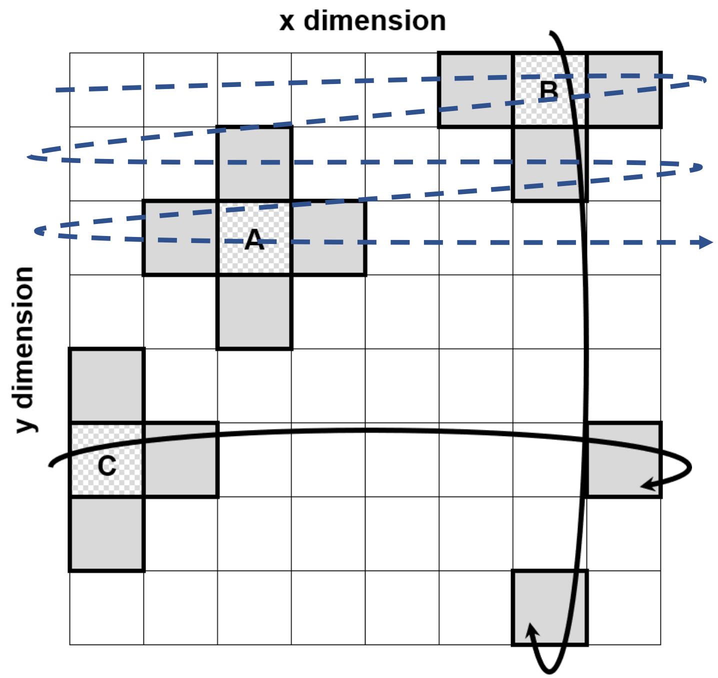
```
void x-solve(unsigned int zone, ...) {
  for (k=0; k<z-dim; k++)
    for (j=0; j<y-dim; j++)
      for (i=0; i<x-dim; i++)
        /* Some matrix-based
           computations */

  /* Several computations in the
     form of loop nests */

}
```

Communication Period: Zone Adjacency

- Adjacent zones
  - 4 neighbors
    - north
    - south
    - east
    - west
- Exchange border values between adjacent zones



Communication Period: Intra-Zone Parallelism

- Processing of zone borders

```
for (zone=0; zone<NUM-ZONES; zone++) {
  east-zone = adjacency-east[zone]
  north-zone = adjacency-north[zone];

  copy-face(tmpEast, mesh[east-zone]);
  copy-face(tmpNorth, mesh[north-zone]);

  compute-border(mesh[zone], tmpEast, tmpNort

  copy-face(mesh[east-zone], tmpEast);
  copy-face(mesh[north-zone], tmpNorth);
}
```

```
void compute-border(...) {

  for (k=0; k<z-dim; k++)
    for (j=0; j<y-dim; j++)
      for (i=0; i<x-dim; i++)
        /* Some matrix-based
           computations */
```

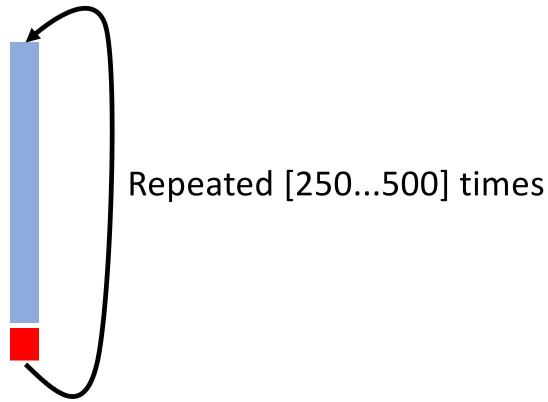
```
void copy-face(...) {

  for (k=0; k<z-dim; k++)
    for (j=0; j<y-dim; j++)
        /* Some matrix-based
           computations */
```

Summary: Computation and Communication Periods, Sources of Parallelism

- Two levels of parallelism:
  - Coarse grain parallelism: INTER-ZONE parallelism
  - Fine grain parallelism : INTRA-ZONE parallelism

- Parallelism is repeated many times
  - Computation Period
    - INTER-ZONE: mapped to CPUs **and** GPUs
    - INTRA-ZONE: mapped to CPUs **or** GPUs
  - Communication Period
    - INTRA-ZONE: mapped to CPUs **or** GPUs



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NPB-MZ Hybrid Design and Implementation

- Hybrid Execution Model: OpenMP+CUDA
  - Computing Unit Abstraction
    - `libCU-rtl`
  - Address Space Abstraction
    - `libAS-rtl`
  - Work Distribution Schemes
    - `libSCHEDULING-rtl`
- NPB-MZ Hybrid Parallelization

Computing Units (I)

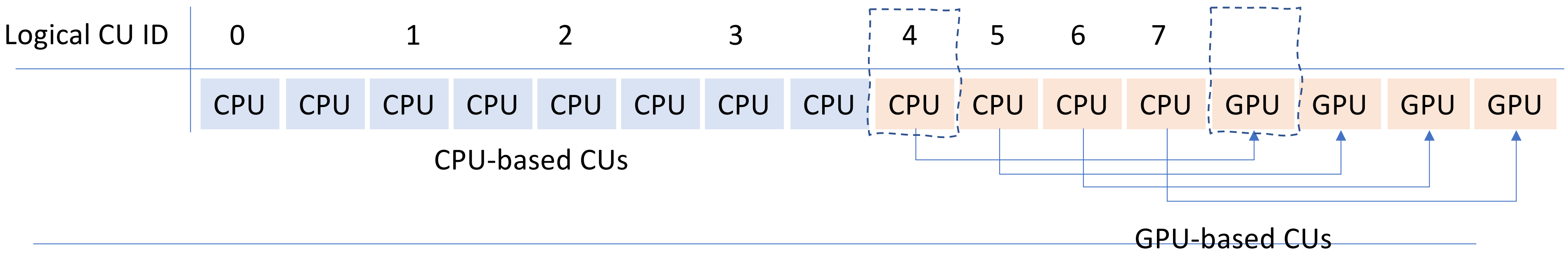
- Computing Units (CUs)
  - Logical view of all available CPUs and GPUs
  - A CU can be of type CPU or GPU
    - If CU type is of `CPU`
      - CU maps onto **one or more** physical `<CPU>`
    - If CU type is of `GPU`
      - CU maps to **one pair** of physical `<CPU,GPU>`
        - The CPU controls the GPU

- Computing Units (CUs)
  - NCU = number of available CUs
  - CUs are numbered from 0 up to the NCU-1
    - NCPU = Number of CPU-based CUs
    - NGPU = Number of GPU-based CUs
    - `[0 .. NCPU-1]` correspond to CPU-based CUs
    - `[NCPU .. NCU-1]` correspond to GPU-based CUs
- CUs and Threads
  - We run as many threads as the number of NCU

Computing Units (II)

- Example:
  - Execution with 8 CUs = 4 x CPU-based CUs + 4 GPU-based CUs
    - CPU-based CU = 2 x CPUs
    - GPU-based CU = CPU + GPU

    => 12 physical CPUS + 4 physical GPUS
  - 12 threads mapped onto 12 physical CPUs

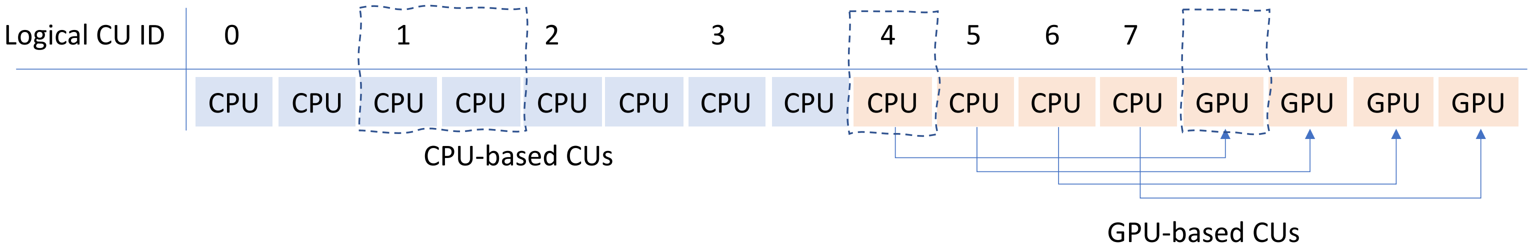


Hybrid Execution Model: OpenMP + CUDA

- How do we introduce the abstraction of a CU in OpenMP+CUDA?
  - Implement runtime support to bridge the two execution models
    - `libCU-rtl`
- Parallelism for CUs is created through `omp parallel` construct
  - 1 CPU-based CU: 1 OpenMP thread
  - 1 GPU-based CU: 1 OpenMP thread that controls a device
- CUs are formed through `OMP_PLACES`
- Name spaces for CU, OpenMP threads and CUDA devices
  - Logical CU id ⇔ OpenMP Thread id
    - `OpenMP Thread id = CU id`
  - Logical CU id ⇔ CUDA Device id
    - `CUDA Device id = CU id – NCPU`

CUs definition and OpenMP thread places

- Example
  - `OMP_PLACES = “{0, 1}, {2, 3}, {4, 5}, {6, 7}, {8}, {9}, {10}, {11}”`
  - `OMP_PROC_BIND=TRUE`
  - NCPU = 4 with 2 inner CPUs
  - NGPU = 4
  - Logical CU ids match OpenMP logical thread ids



Runtime Support for CUs

- Small set of runtime primitives
  - RUNTIME::gpus
  - RUNTIME::cpus
  - RUNTIME::isGPU()
  - RUNTIME::isCPU()
  - RUNTIME::GPU()
  - RUNTIME::CPU()
  - RUNTIME::innerCPUs()
  - RUNTIME::getTask()
  - RUNTIME::getCU()
  - RUNTIME::setCU()
  - RUNTIME::commitTask()
  - RUNTIME::executeTask()
  - RUNTIME::synchronize()

Number of GPU-based CUs and CPU-based CUs

Query if CU is mapped onto CPU or GPU

Get a CPU/GPU id in OpenMP/CUDA

Get a number of inner threads for a CPU-based CU

Get a task mapped to the current CU

Get/set the CU logical ID

Start/end of the execution of an assigned task

Synchronize with corresponding device if CU is mapped to a GPU

Code Transformation for CU support

CU parallelism

```
#pragma omp parallel \
              num_threads(RUNTIME::cpus+RUNTIME::gpus)
{
  unsigned int task;
  task = RUNTIME::getTask();
  while (task!=NO_TASK) {

    unsigned int CU = RUNTIME::getCU();

    RUNTIME::executeTask()

    /* COMPUTATIONS */

    if (RUNTIME::isGPU(CU)) RUNTIME::synchronize();

    RUNTIME::commitTask();

    task = RUNTIME::getTask();
  } // while
} // parallel
```

```
OMP_PROC_BIND=TRUE
OMP_PLACES = "{0, 1},{2, 3},{4, 5},{6, 7},
              {8},   {9},   {10},  {11}"
```

CU computations

```
  unsigned int CU = RUNTIME::getCU();
  if (RUNTIME::isCPU(CU)) {
    NT = RUNTIME::innerCPUs();
#pragma parallel num_threads(NT) proc_bind(master)
{
    /* COMPUTATIONS */

} // parallel

  }
  else if (RUNTIME::isGPU(CU)) {
    cudaSetDevice(RUNTIME::GPU(CU));
    some-GPU-kernel-1<<<grid, block, shared>>>(...);
  }
```

Distributed Address Space: OpenMP + CUDA

- How do we introduce the abstraction of a AS in OpenMP+CUDA?
  - Implement runtime support to bridge the two execution models
    - `libAS-rtl`
- Several Address Spaces (AS)
  - Host
  - Devices
- Name space for AS
  - `[0...NCPU-1]` => HOST
  - `[NCPU...NGPU-1]` => DEVICES
- Monitor data placement
  - Maintain a map of data structures and AS

Runtime Support for Data Placement

- Small set of runtime primitives
  - PLACEMENT::getAS()
  - PLACEMENT::alloc()
  - PLACEMENT::migrate()
  - PLACEMENT::copy()
  - PLACEMENT::isGPU()
  - PLACEMENT::isCPU()

Determine AS for a memory region (e.g.: a zone)

Memory allocation (e.g.: a zone) in an AS

Migrate a memory (e.g.: a zone) to an AS

Generate a copy of a zone to an AS

Query if memory (e.g.: a zone) is mapped onto CPU or GPU

Work Distribution: OpenMP + CUDA

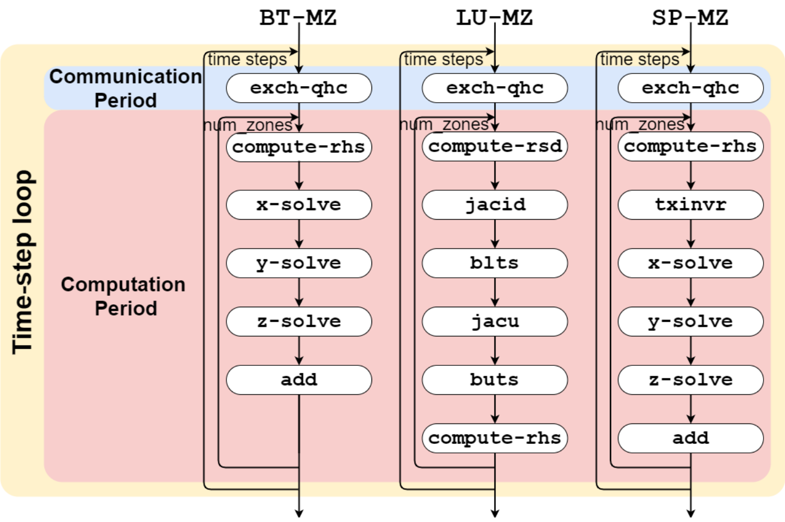
- OpenMP work distribution schemes are not suitable
  - TASKS: you do not have control over which thread will execute a task
  - LOOPs: available loop schedulers are not suitable, not designed for heterogeneity
    - STATIC, DYNAMIC, GUIDED
- Implement a runtime support to bridge the two execution models at the application level
  - libSCHEDULING-rtl

Runtime Support for Scheduling

- Assume tasks are numbered from `[0...`N_{tasks}`-1]`
  - Inputs for schedulings
    - N_{tasks}
    - `NCPU`
    - `NGPU`
- SCHEDULING-rtl
  - SCHEDULING::Static()
  - SCHEDULING::Dynamic()
  - SCHEDULING::pcf-Static()
  - SCHEDULING::pcf-Guided()
  - SCHEDULING::ClusteredGuided()

Computation Period: Code Transformation

- INTER-ZONE parallelism



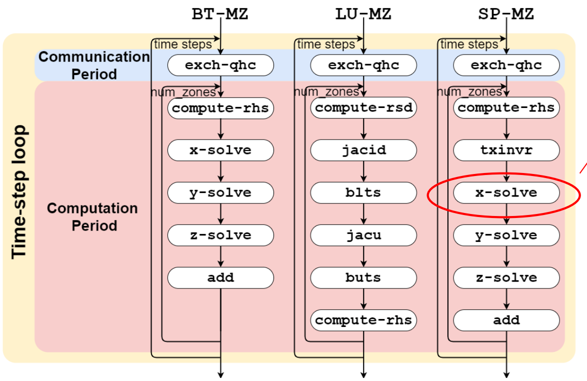
- Example: SP-MZ

```
   SCHEDULE::Static(NUM_ZONES, RUNTIME::cpus, RUNTIME::gpus);
#pragma omp parallel \
            num_threads(RUNTIME::cpus+RUNTIME::gpus)
{
  unsigned int task;
  task = RUNTIME::getTask();
  while (task!=NO_TASK) {
    unsigned int zone = task;

    unsigned int CU = RUNTIME::getCU();
    if (PLACEMENT::getAS(mesh[zone])!=CU) PLACEMENT::migrate(mesh[zone], CU);

    RUNTIME::executeTask();

    compute-rhs(zone, ...);
    txinvr(zone, ...);
    x-zolve(zone, ...);
    y-solve(zone, ...);
    z-solve(zone, ...);
    add(zone, ...);

    if (RUNTIME::isGPU(CU)) RUNTIME::synchronize();

    RUNTIME::commitTask();
    task = RUNTIME::getTask();
  } // while
} // parallel
```

OMP_PROC_BIND=TRUE

Computation Period: Code Transformation

- INTRA-ZONE parallelism




```
void x-solve(unsigned int zone, ...) {
  unsigned int CU = RUNTIME::getCU();
  if (RUNTIME::isCPU(CU)) {
    NT = RUNTIME::innerCPUs();
#pragma parallel for schedule(static)\
        num_threads(NT) proc_bind(master)
    for (k=0; k<z-dim; k++)
      for (j=0; j<y-dim; j++)
        for (i=0; i<x-dim; i++)
          /* Some matrix-based
             computations */
  }
  else if (RUNTIME::isGPU(CU)){
    x-xolve-kernel-1<<<grid, block, shared>>>(zone,...);
  }

  /* Several other computations computations in the
     previous form */

}
```

Communication Period: Border Processing

```
for (zone=0; zone<NUM-ZONES; zone++) {
  east-zone = adjacency-east[zone]
  north-zone = adjacency-north[zone];
  east-AS = PLACEMENT::getAS(mesh[east-zone]]);
  north-AS = PLACEMENT::getAS(mesh[north-zone]);
  zone-AS = PLACEMENT::getAS(mesh[zone]);

  PLACEMENT::pack-face(tmpEast, east-AS, mesh[east-zone]);
  PLACEMENT::pack-face(tmpNorth, north-AS, mesh[north-zone]);
  if (PLACEMENT::isGPU(zone-AS)) {
    CUDA::setDevice(RUNTIME::GPU(zone-AS)):
    gpu-compute-border<<< grid, block, shared>>>(mesh[zone],
                                                 tmpEast,
                                                 tmpNorth);
  else if (PLACEMENT::isCPU(zone-AS)) {
    cpu-compute-border(mesh[zone], tmpEast, tmpNorth);
  }
  PLACEMENT::unpack-face(tmpEast, east-AS, mesh[east-zone]);
  PLACEMENT::unpack-face(tmpNorth, north-AS, mesh[north-zone]);
}
```

Communication Period: Data Packing

```
void PLACEMENT::pack-face(buffer, zoneAS, mesh-zone) {
  myAS = PLACEMENT::getAS();
  if (myAS!=zoneAS) {
    // remote packing of border data and transfer to myAS
     if (PLACEMENT::isGPU(zoneAS) {
       CUDA::setDevice(RUNTIME::GPU(zone-AS));
       gpu-pack-face<<<grid, block, shared>>>(...);
       CUDA::cudaMemCpy(buffer, ..., cudaDeviceToHost);
     } else if (PLACEMENT::isCPU(zoneAS){
       cpu-pack-face(...);
     }
  } else {
    // pack border data
  }
}
void PLACEMENT::unpack-face(buffer, zoneAS, mesh-zone);
```

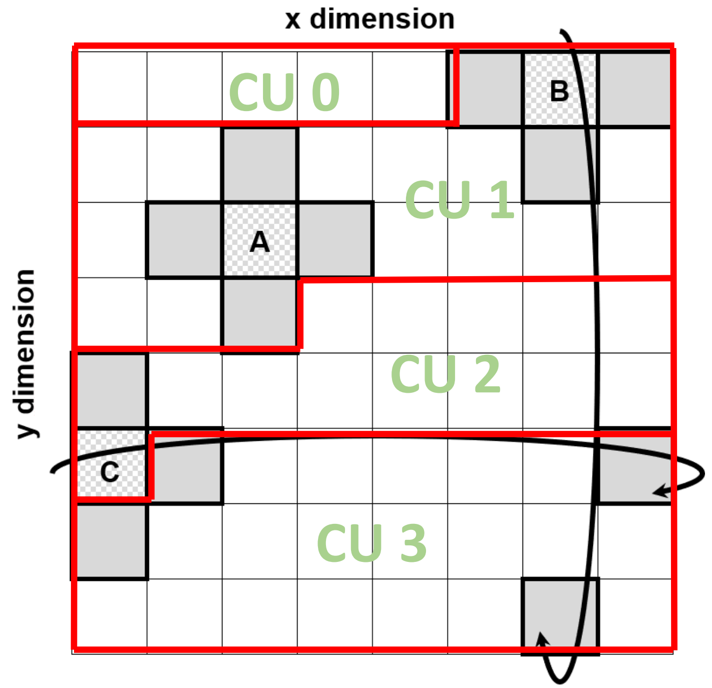
```
void cpu-pack-face(buffer, mesh-zone);
void cpu-unpack-face(buffer, mesh-zone);
```

```
__global__ gpu-pack-face(buffer, mesh-zone);
__global__ gpu-unpack-face(buffer, mesh-zone);
```

- In a hybrid execution the **CUDA::cudaMemCpy** is the source of overhead

Communication Period: Data placement and Communication

- Trade off between the number of data transfers and data placement
  - NCU =4
  - Zone B
    - Assigned to a CU where 1 adjacent zone is assigned to other CUs
  - Zone A
    - Assigned to a CU where all 4 adjacent zones are assigned to the same CU
  - Zone C
    - Assigned to a CU where 3 adjacent zones are assigned to other CUs



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Work Distribution Schemes For OpenMP+CUDA

- Baseline Schedulers
  - STATIC
  - DYNAMIC
- Performance Factor Conversion (PCF) Schedulers
  - PCF-STATIC
  - PCF-GUIDED
- Self Adaptive Schedulers
  - CLUSTERED GUIDED

STATIC scheduler

- Tasks are identified from 0 up to the number of tasks -1
- `NTASKS = NUM_ZONES;`
- `CU-WORK = NTASKS/NCU;`
- If remaining tasks, those are assigned to lower CUs within the numbering
  - CPUs first, then the GPUs
- `<start,end>:` identifies the set of tasks assigned to a CU
  - `start` = initial task
  - `end` = final task
- Maximizes adjacency, so minimizes communications

DYNAMIC scheduler

- Fast CUs (e.g.: GPUs) will tend to get more work
- Slow CUs (e.g.: CPUs) will tend to get less work
- `CHUNK = 1;`
- Memorizes TASK-CU mapping
  - Avoids memory migration overheads
- Breaks adjacency, so will tend to increase the communications

PCF-STATIC scheduler

- Variant of STATIC scheduler
- Based on a Performance Conversion Factor (PCF)
  - PCF = relation between the computational power of CPU-based CUs and GPU-based CUs
  - Example
    - PCF = 2, means that GPU-based CUs are twice faster than CPU-based CUs
    - PCF = 1, means both CPU and GPU based CUs have same computation power

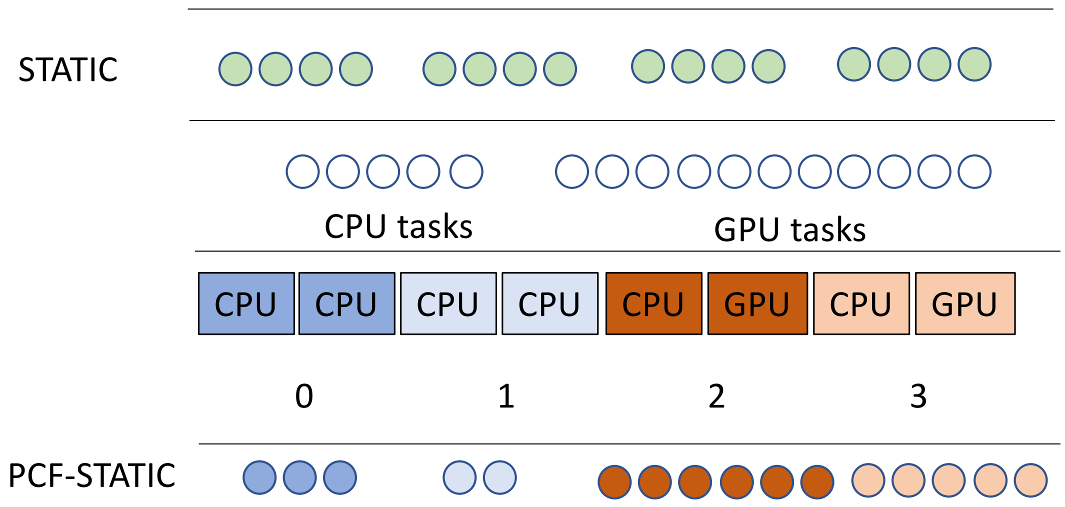
PCF-STATIC scheduler

- Divide in two parts the set of tasks
  - `NTASKS = PCF x CPU-TASKS + CPU-TASKS = (PCF+1) x CPU-TASKS`
  - `GPU-TASKS = NTASKS – CPU-TASKS`
- Apply STATIC over `CPU-TASKS` and among all CPU-based CUs
- Apply STATIC over `GPU-TASKS` and among all GPU-based CUs

- Maximizes adjacency, so minimizes communications

PCF-STATIC scheduler

- Example:
  - PCF = 2
  - NCU = 4
    - CPU-based CU = 2
    - GPU-based CU = 2
  - NTASKS = 16
  - CPU-TASKS = 5
  - GPU-TASKS = 11

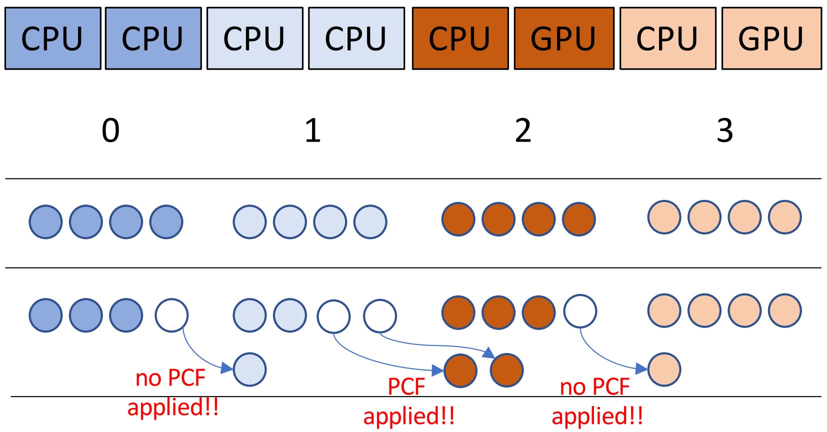


<start,end>: interval of tasks assigned to a CU

STATIC:	<0,3>	<4,7>	<8,11>	<12,15>
PCF-STATIC:	<0,2>	<3,4>	<5,10>	<11,15>

PCF-GUIDED scheduler

- Initially, apply a STATIC scheduling
- Execute and monitor task execution time
- Adapt the work distribution so that it gets balanced
    - ALL-WORK = addition of all task execution times factorized with PCF
    - WORK-CU = ALL-WORK / NCU
    - Keep the assigned work per CU close to WORK-CU
- Maximizes adjacency, so minimizes communications



<start,end>: interval of tasks assigned to a CU

STATIC: <0,3> <4,7> <8,11> <12,15>
PCF-GUIDED: <0,2> <3,5> <6,10> <11,15>

PCF-GUIDED scheduler

- Samples of execution time are taken from `RUNTIME::executeTask()` and `RUNTIME::commitTask()`
- Code scheme for work balance

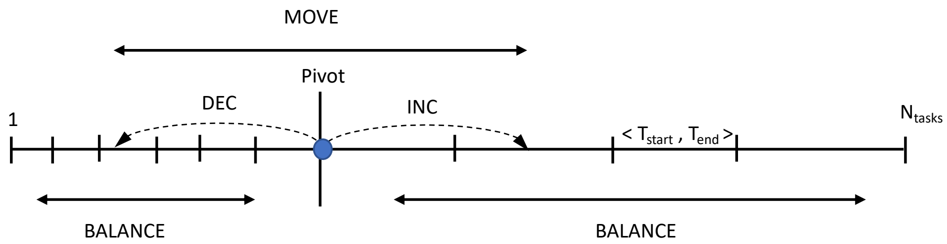
```
for cu = 0, NCU-1
  WORK[cu]= "add tasks execution times"

for cu = 0, NCU-2
  while WORK[cu]>WORK-CU /* With some threshold */
    <start[cu],end[cu]-->
    WORK[cu] -= "execution time of end task"
    WORK[cu+1] += "execution time of end task refactorized with PCF"

  while WORK[cu]<WORK-CU /* With some threshold */
    <start[cu],end[cu]++>
    WORK[cu] += "execution time of end task refactorized with PCF"
    WORK[cu+1] -= "execution time of end task"

  start[cu+1] = end[cu]
```

```
#pragma omp parallel \
            num_threads(RUNTIME::cpus+RUNTIME::gpus)\
            proc_bind(true)
{
  unsigned int task;
  task = RUNTIME::getTask();
  while (task!=NO_TASK) {
    unsigned int zone = task;

    unsigned int CU = RUNTIME::getCU();
    if (PLACEMENT::zonePlacement[zone]!=CU &&
        RUNTIME::isGPU(CU))
      PLACEMENT::migrateZone(CU);

    RUNTIME::executeTask();

     /* Computational Stages */

    if (RUNTIME::isGPU(CU)) RUNTIME::synchronize();

    RUNTIME::commitTask();

    task = RUNTIME::getTask();
  } // while
} // parallel
```

g for

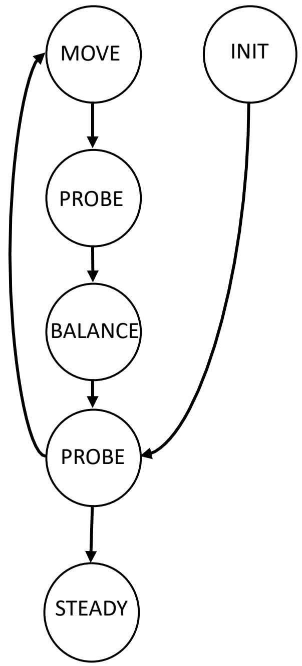
CLUSTERED GUIDED scheduler

- Set of tasks is divided in two clusters
  - One for CPU-based CUs, the other for GPU-based CUs
  - PIVOT: separating point for the two clusters
- At each instance of the scheduler, the PIVOT moves left/right to balance the work assigned to each cluster
  - Sort of a dichotomic search
- The scheduler balances the work distribution within each cluster



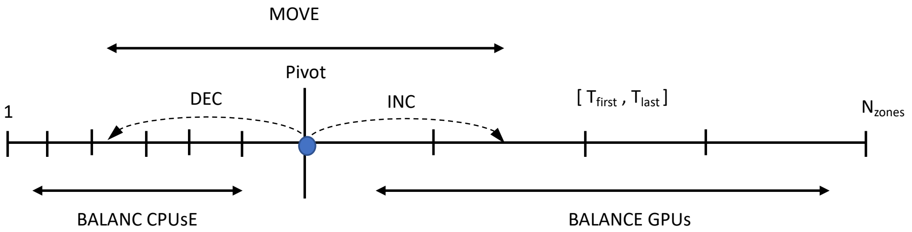
CLUSTERED GUIDED scheduler

- The scheduler evolves at runtime, switching between different states:
  - `INIT`: PIVOT is initialized (e.g.: PIVOT=NCPU). Applies a STATIC scheduling in both clusters.
  - `MOVE`: Moves PIVOT, according to where the maximum execution time has occurred.
  - `PROBE`: Samples execution time for each CU. Determines the maximum value observed in each cluster.
  - `BALANCE`: Applies a PCF-GUIDED scheduler with PCF=1 to each cluster.
  - `STEADY`: Records final configuration for work distribution.



CLUSTERED GUIDED scheduler

<u>Data Structures:</u>
Pivot: Index that indicates the border between tasks assigned to CPUs and tasks assigned to GPUs
DEC: Value to decrement the Pivot
INC: Value to inclement the Pivot
TaskTime []: Vector of N_{zones} elements, each one describing the execution time of a task
CUtime []: Vector of N_{CUs} elements, each one describing the execution time of CU
FirstTask []: Vector of N_{CUs} elements, each one describing the T_{first} task assigned to a CU
LastTask []: Vector of N_{CUs} elements, each one describing the l_{Tast} task assigned to a CU



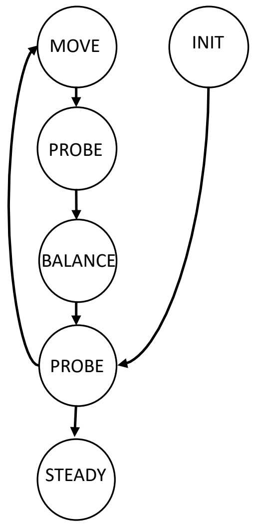
<u>MOVE:</u>
T_{cpu} = max time for CPUs
T_{gpu} = max time for GPUs
if $T_{cpu} > T_{gpu}$
 INC = INC / 2
 goingLEFT = false
 goingRIGHT = true
 pivot += INC

if $T_{gpu} > T_{cpu}$
 DEC = DEC / 2
 goingLEFT = true
 goingRIGHT = false
 pivot-= DEC

<u>BALANCE (CPUs/GPUs):</u>
for cu = 1 , N_{CUs}
 TotalWork = CUtime[cu]

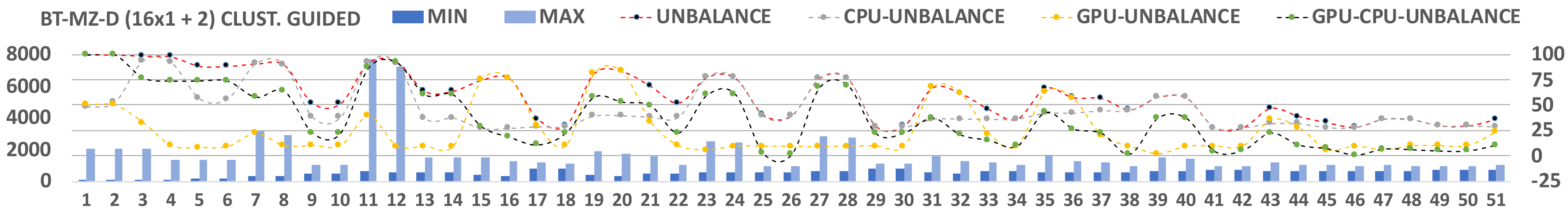
WorkPerCU = TotalWork / N_{CUs}
for cu = 1 , N_{CUs}
 First = FirstTask[cu]
 Last = LastTask[cu]
 Work = $\sum_{First}^{Last} T_i$
 DIFF = | Work - WorkPerCU |
 if (Work < WorkPerCU && **DIFF > TH**)
  while (Work < WorkPerCU) Last++; Work =+ T_{last}
 else if (Work > WorkPerCU && **DIFF > TH**)
  while (Work > WorkPerCU) Last--; Work =- T_{last}
 LastTask[cu] = Last
 FirstTask[cu] = Last + 1

<u>INIT</u>:
Pivot = N_{CPUs}
INC = DEC = N_{tasks} / 2

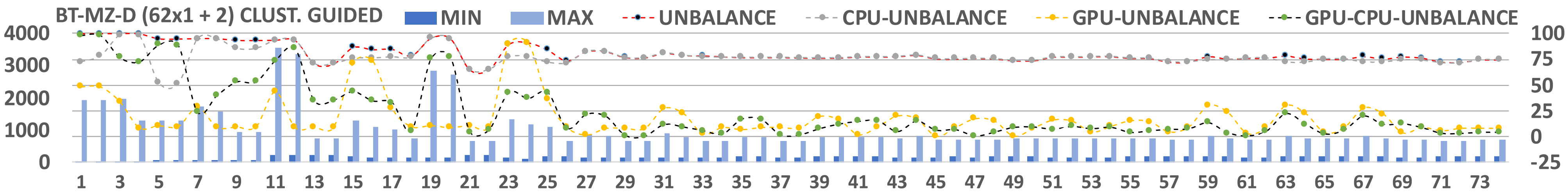


Number of steps to STEADY state: $log_2(N_{tasks})\ x\ 4$

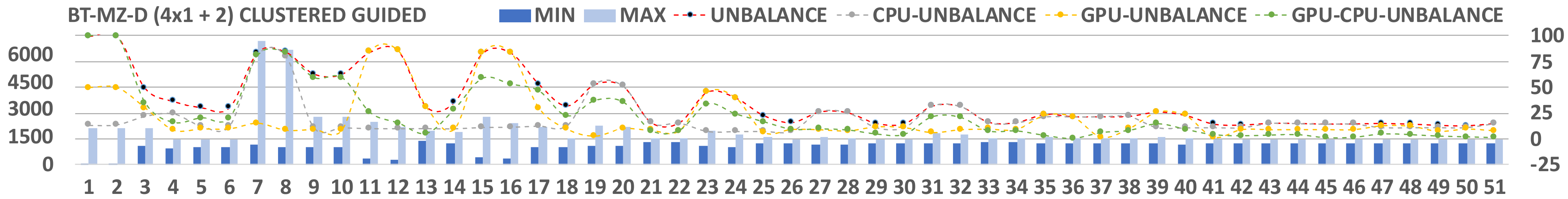
Examples of Clustered Guided



Examples of Clustered Guided



Examples of Clustered Guided



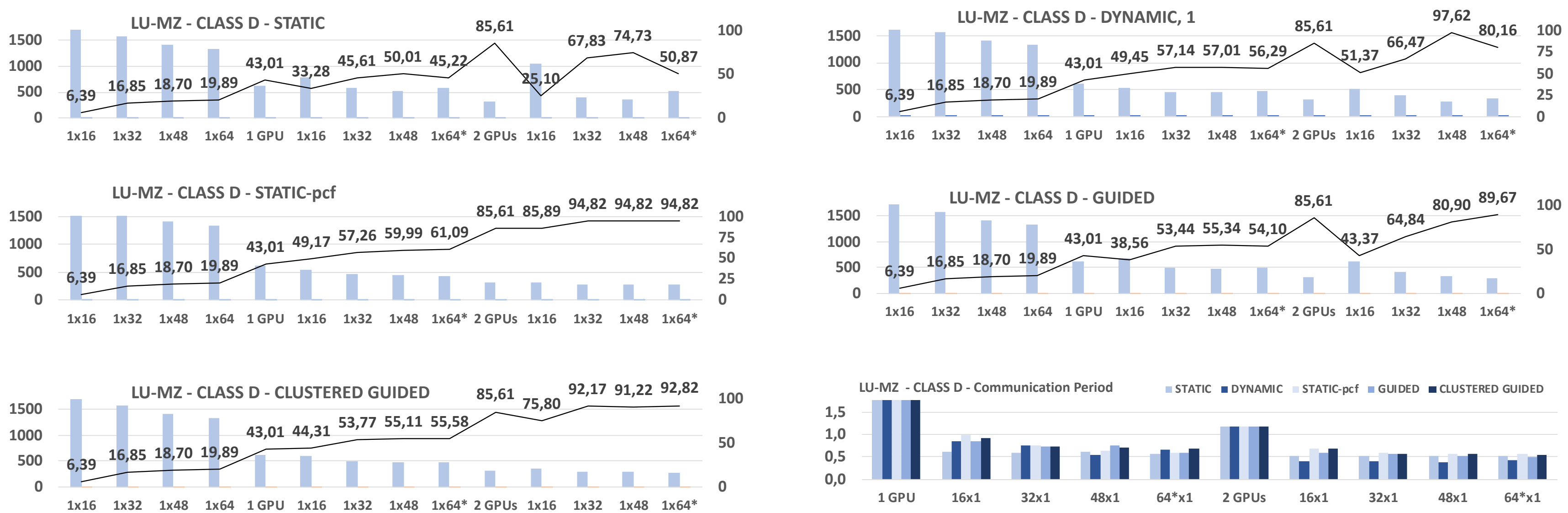
Outline

- Analysis, parallelism characterization of NAS-MZ suite of benchmarks
- NPB-MZ Hybrid Design and Implementation
- Work distribution schemes for hybrid executions
- Evaluation Results

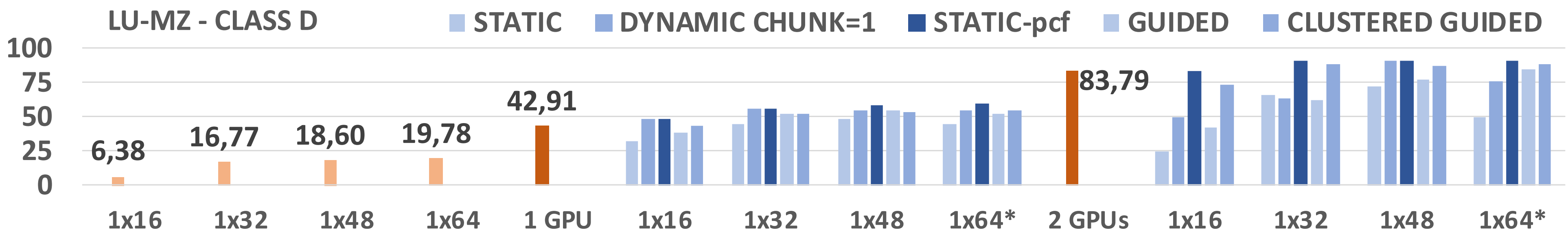
Environment

- AMD CTE @ BSC
  - AMD EPYC 7742 @ 2.250GHz (64 cores)
  - 2 x GPU AMD Radeon Instinct MI50 with 32GB
- Software stack
  - GCC 8.3.1–4
  - Radeon Open Compute (ROCm) Runtime software stack 3.5.0
- Hybrid NPB-MZ implementation
  - Parallel CUDA multi-gpu version of the NPB-MZ in C++
  - Parallel (OpenMP) implementation in Fortran of NPB-MZ
  - Runtime Libraries: `libCU-rtl`, `libPLACEMENT-rtl`, `libSCHEDULING-rtl`

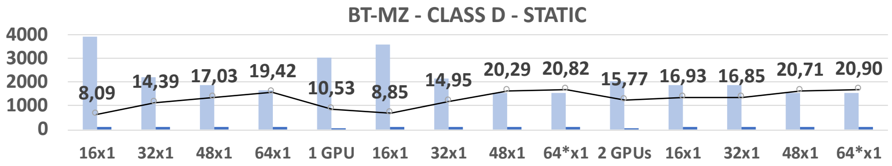
LU-MZ: Compute and Communication

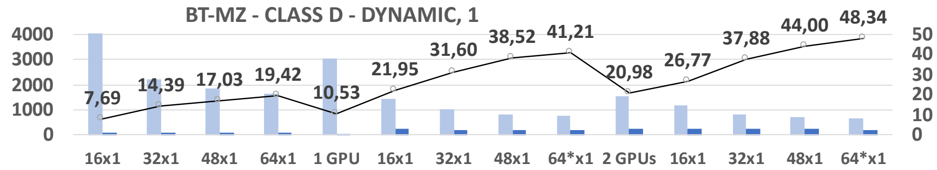


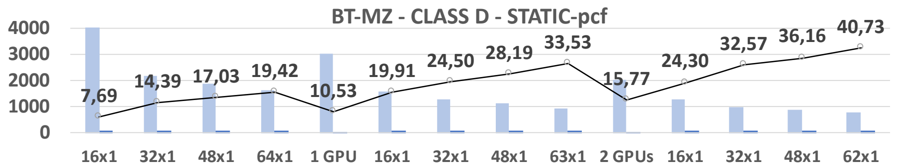
LU-MZ: Overall Performance

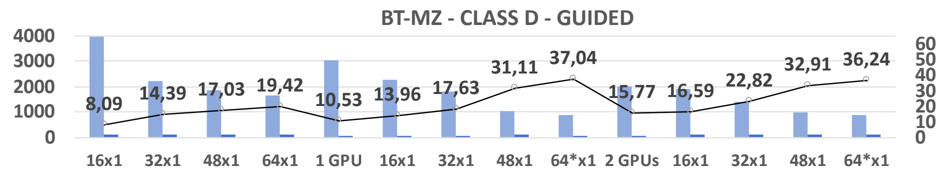


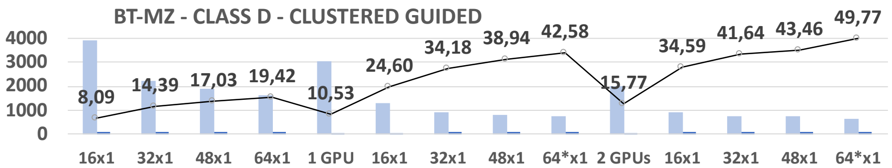
BT-MZ: Compute and Communication

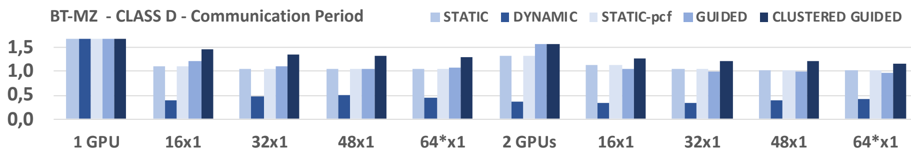




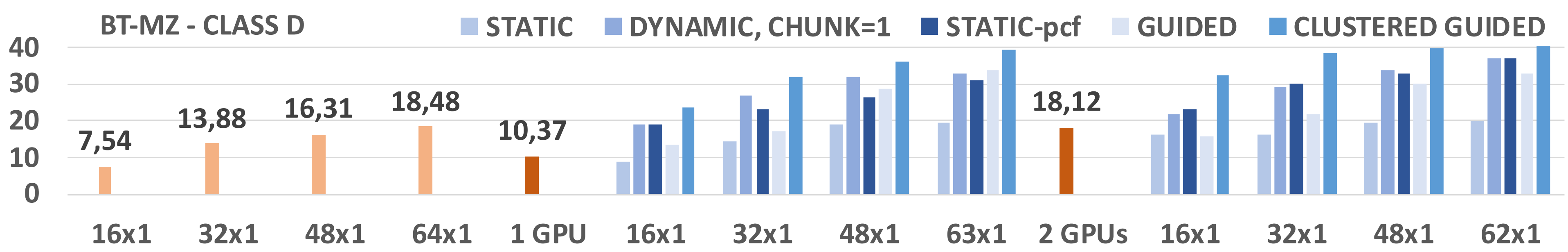




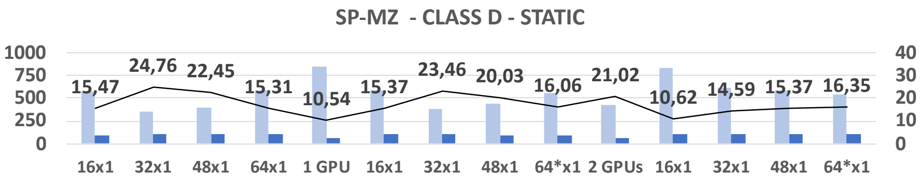


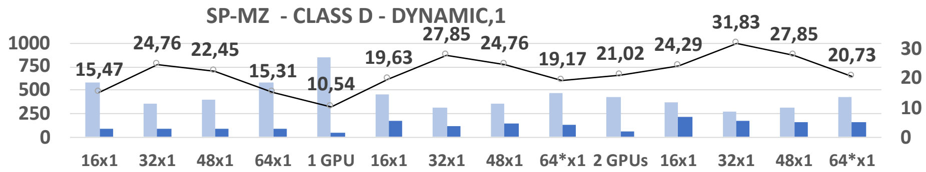


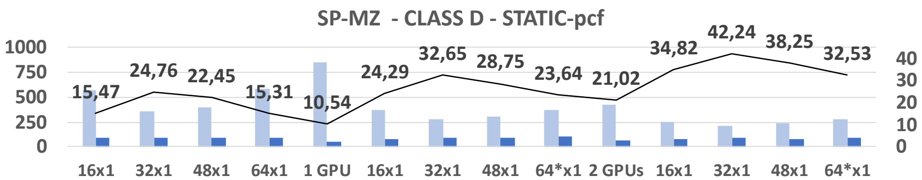
BT-MZ: Overall Performance

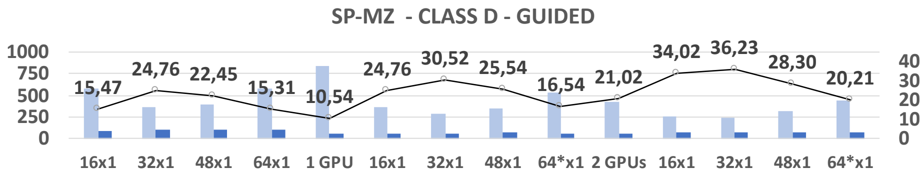


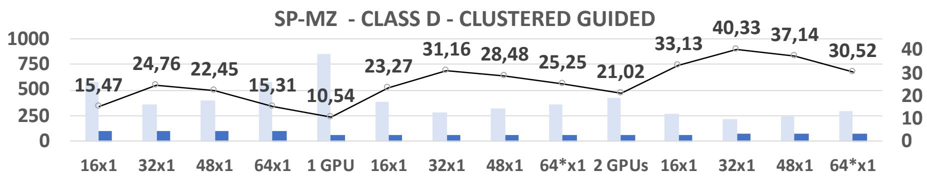
SP-MZ: Compute and Communication

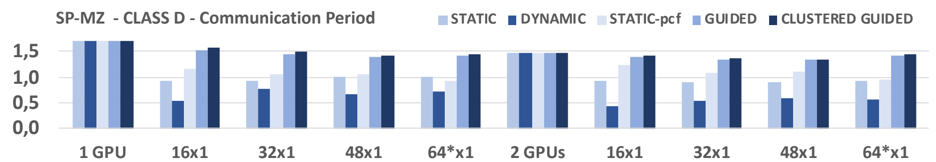




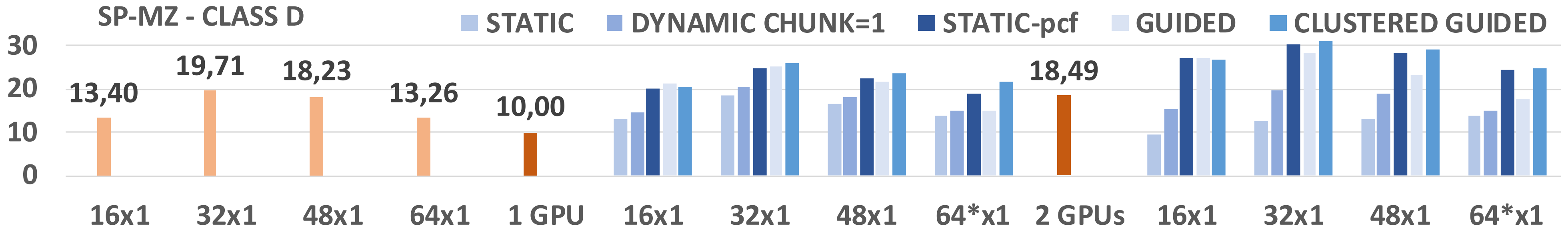








SP-MZ: Overall Performance



Conclusions

- Case of study for hybrid computing (NPB-MZ), using OpenMP+CUDA
  - Methodology based on runtime implementation for bridging the two execution models
    - CU abstraction, AS abstraction at the programming model level
    - Work distribution schemes for hybrid executions
      - Based on rough performance comparison (PFC)
      - Monitoring task execution times (Clustered Guided)
- In general, the more GPUs in place, less space for using the CPUs
  - From a pure “FLOPS” perspective, we should try to use the CPUs for other purposes
    - Design runtime systems that solve programming limitations: memory allocators for dynamically changing data layouts, work distribution schemes, even code optimization ...

Heterogeneous Computing for Scientific Applications

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