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A performance-oriented comparative study of the Chapel high-productivity language to conventional programming environments

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Background

- Heterogeneity (CPU-GPU) and size of **modern supercomputers** (millions of cores) [1]:

Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Supercomputer Fugaku** - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442,010.0	537,212.0	29,899
2	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148,600.0	200,794.9	10,096
3	**Sierra** - IBM Power System AC922, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94,640.0	125,712.0	7,438

Top 3 of the Top500 bi-annual ranking (Nov. 2021)

- Emergence of **high-productivity programming languages** [2]:
  - Chapel, X10, Fortress, *etc.*

Motivations and objectives

- **Compare Chapel to conventional parallel programming libraries**, in terms of performance...
  - ➢ on both shared- and distributed-memory systems;

- Illustrate the programming effort in each parallel environment... and **provide a sense of "productivity"**;

- **Provide a useful data point** using shared- and distributed-memory multi-core systems for supercomputer programmers…
  - ➢ through a well-known and complete parallel application.

Outline

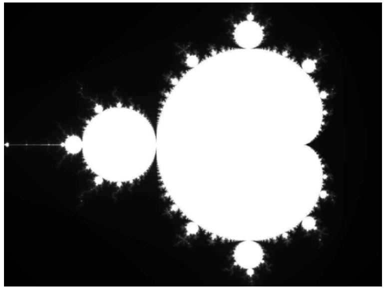
- Formulation of the test-case
- Parallel programming environments and implementations
  - OpenMP
  - Chapel
  - MPI
  - Hybrid MPI+OpenMP
- Experimental evaluation
  - Testbed
  - Shared-memory experiments
  - Distributed-memory experiments
  - Parallel overheads
- Conclusions and future works

Test-case: the Mandelbrot set

It is defined as the set of complex numbers $c = a + ib \in \mathbb{C}$ such that the sequence $(z_n)_{n \in \mathbb{N}} \subset \mathbb{C}$ defined by

$$z_0 = 0, \qquad z_{n+1} = z_n^2 + c, \tag{1}$$

remains bounded in $\mathbb{C}$.



Monochrome Mandelbrot set

```
function Compute_pixel(a, b) :
    x = y = 0;
    n = 0;
    while x^2 + y^2 < 4 and n < N do
        t = x;
        x = x^2 − y^2 + a;
        y = 2ty + b;
        n = n + 1;
    end
    I(a, b) = n/N;
end
```

Pseudo implementation of the Mandelbrot set computation

- Embarrassingly parallel application, due to the **independency between pixels**;
- **Domain decomposition** method, **along the lines**;
- **Static decomposition;**
- Lines are mapped in **round-robin fashion.**

Open Multi-Processing (OpenMP)

- OpenMP is an **application programming interface**;

- It is designed for:
  - **Ease of programming**;
  - **High performance**, and;
  - **Portability;**

  … only on shared-memory systems;

- OpenMP supports a **multithreaded execution**, through a fork-join model;

- It provides **simple high-level constructs**, for work-sharing among threads for example;

- For more details [3]: https://www.openmp.org/.

```
function Compute_image_omp() :
    #pragma omp parallel for schedule(static, 1);
    for a = 0 to nb_lines do
        for b = 0 to nb_columns do
            Compute_pixel(a, b);
        end
    end
end
```

Pseudo OpenMP implementation of the Mandelbrot set computation

Cascade High Productivity Language (Chapel)

- Chapel is a **PGAS-based language**;

- It is designed for:
  - **Ease of programming**;
  - **High performance**, and;
  - **Portability**;

- Chapel supports a **multithreaded execution model** and allows:
  - **Data/task parallelism**;
  - **Locality control**, *etc;*

- Here Chapel follows the **SPMD execution model**;

- For more details [4]: https://chapel-lang.org/.

```
function Compute_image_chpl() :
    coforall loc = 0 to nb_locales do
        on loc do
            coforall rank = 0 to nb_tasks do
                for a = loc.id + rank * nb_locales to
                  nb_columns by
                  nb_tasks * nb_locales do
                    for b = 0 to nb_columns do
                        Compute_pixel(a, b);
                    end
                end
            end
        end
    end
end
```

Pseudo Chapel implementation of the Mandelbrot set computation

Message Passing Interface (MPI)

- Message-passing **application programming interface**;
- MPI is widely used is the academic and industrial areas:
  - **Portability**;
  - **High performance**, and;
  - **Standardization**;
- MPI defines a **communication protocol among processes** running on distributed-systems:
  - Point-to-point or **two-sided**;
  - **One-sided**;
- Here MPI follows the **SPMD execution model**;
- For more details [5]: https://www.open-mpi.org/.

```
for l = rank to nb_lines by commsize do
    Compute_line(l);
    if rank ≠ 0 then
        MPI_Send(/*args*/);
    else
        MPI_Recv(/*args*/);
    end
end
```

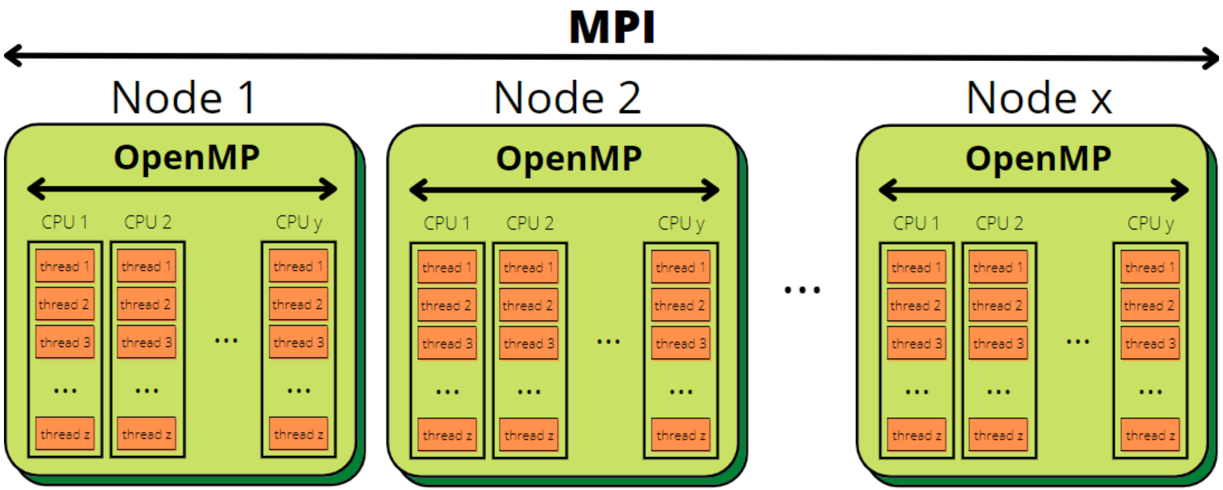
Pseudo MPI two-sided implementation of the Mandelbrot set computation

```
MPI_Win_create(win);
MPI_Fence();
for l = rank to nb_lines by commsize do
    Compute_line(l);
    if rank ≠ 0 then
        MPI_Put(/*args*/);
    end
    MPI_Fence();
end
```

Pseudo MPI one-sided implementation of the Mandelbrot set computation

Hybrid MPI+OpenMP

- OpenMP and MPI are complementary…
  - OpenMP is used for intranode parallelism;
  - MPI is used for distribution across nodes (1 MPI process/node).



Hybrid MPI+OpenMP approach

Experimental environment

- Grid’5000 French national testbed [6]:
  - **6 computer nodes** allocated;
  - 32 **AMD EPYC 7301 CPUs @2.20GHz** / nodes;
  - 25 Gbps **Intel Ethernet Controller XXV710 network**;

- gcc 10.2.1, Open MPI 4.1.0, OpenMP 4.5, Chapel 1.25.0;

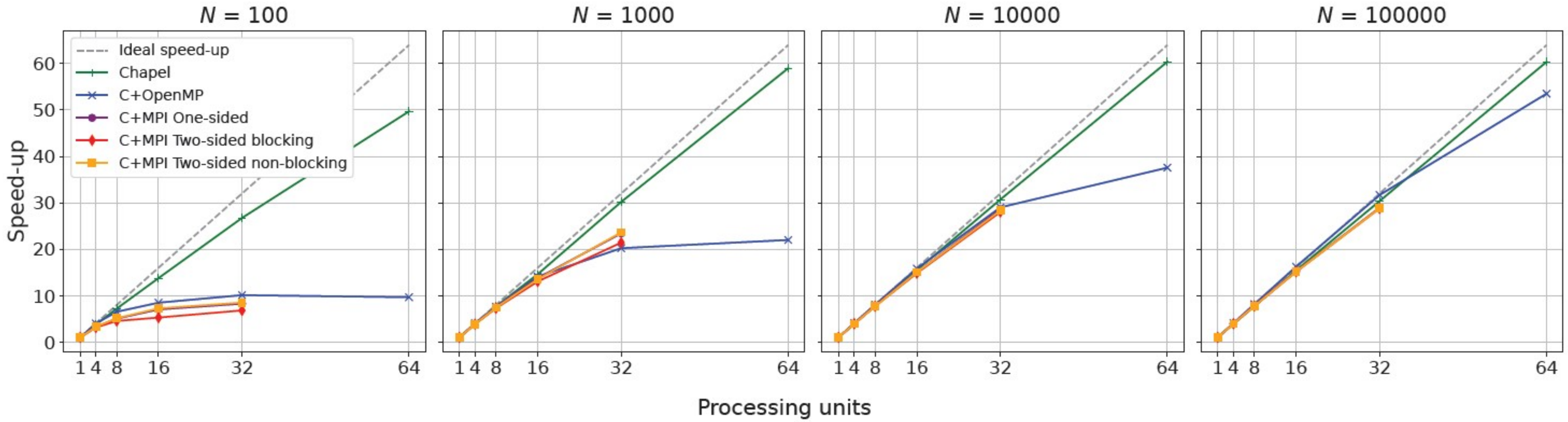
- Compile options:
  - gcc `-O2` optimization flag;
  - Chapel `--fast` optimization flag;

- Chapel multi-locale configuration:

Variable	Value
CHPL_RT_NUM_THREADS_PER_LOCALE	64
CHPL_TARGET_CPU	*native*
CHPL_HOST_PLATFORM	*linux64*
CHPL_LLVM	*none*
CHPL_COMM	*gasnet*
CHPL_COMM_SUBSTRATE	*udp*
GASNET_PSM_SPAWNER	*ssh*

Shared-memory experiments

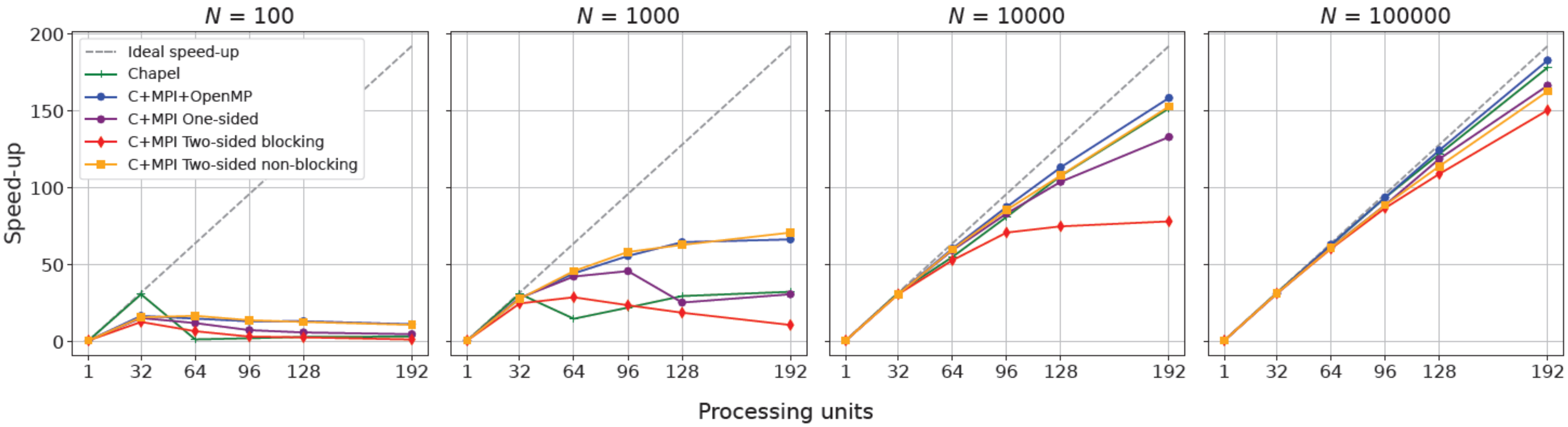
- Fixed image size : 768x1024 pixels;
- **1 to 32 CPU cores** (**hyperthreading enabled**, 2 threads/core);
- N controls the granularity;
- 5 different implementations.



Speed-up achieved by all five shared-memory implementations

Distributed-memory experiments

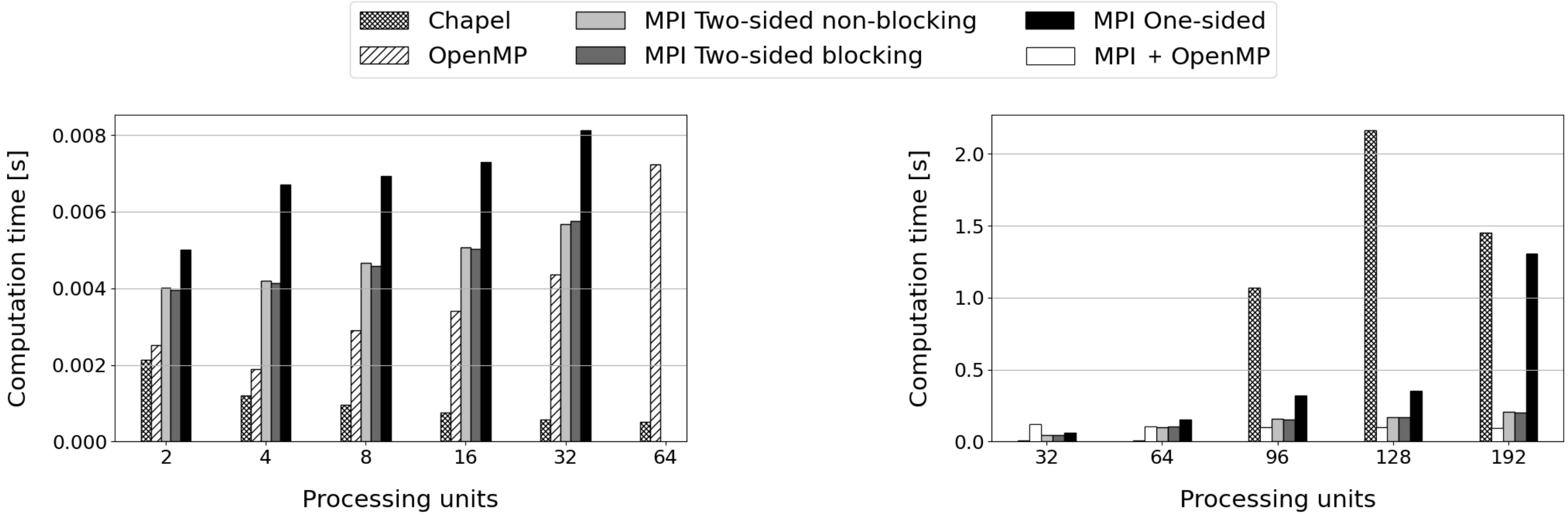
- Fixed image size : 3840x5120 pixels;
- **1 to 192 CPU cores** (hyperthreading disabled);
- N controls the granularity;
- 5 different implementations.



Speed-up achieved by all five distributed-memory implementations

Parallel overheads

- **N=1** to highlight the communication overheads;
- Fixed image size: 768x1024 (shared) and 3840x5120 (distributed);
- Chapel relies by default on the *qthreads* tasking layer [7].



Computational overhead measured by all implementations in shared- (left) and distributed-memory (right) experiments

Conclusions and future works

- Chapel...
  - **outperforms its counterparts in shared-memory**, and;
  - **competes with hybrid MPI+OpenMP** in distributed-memory.

- The *qthreads* default tasking layer of Chapel could explain these performances…
  - although it seems to **suffer from the lack of high-performance network** between nodes.

- We plan to investigate…
  - **more complex benchmarks**, involving message aggregation and data replication;
  - other Chapel features, such as **distributed iterators**, **specific data structures**, *etc*.

Some references

[1] TOP500 ranking. https://www.top500.org/

[2] E. Lusk and K. Yelick. 2007. Languages for High-Productivity Computing:the DARPA HPCS Language Project. *Parallel Processing Letters* 17 (2007), 89–102.

[3] OpenMP API. *The OpenMP API specification for parallel programming*. https://www.openmp.org

[4] Open MPI. *Open MPI: Open Source High Performance Computing*. https://www.open-mpi.org

[5] Chapel. *The Chapel Parallel Programming Language*. https://chapel-lang.org

[6] Grid'5000. https://www.grid5000.fr

[7] K. Wheeler, R. Murphy, D. Stark, and B. Chamberlain. 2011. The Chapel Tasking Layer Over Qthreads.

Thank you for your attention !

Any question ? Any remark ?

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