L4: Experimental Design, Profiling, and Performance/Energy Optimization

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Master Calcul Haute Performance et Simulation - GLHPC | UVSQ

Experimental Design, Profiling, and Performance/Energy Optimization

Plot Example - Intro

In the following slides, you will be shown a series of plots; mainly taken from the PPN course reports of previous students.

For each plot:

- Try to understand what is represented
- Explain what you observe
- Give a **definitive** conclusion from the data shown

Raise your hands when ready to propose an explanation.

Plot Example (1)

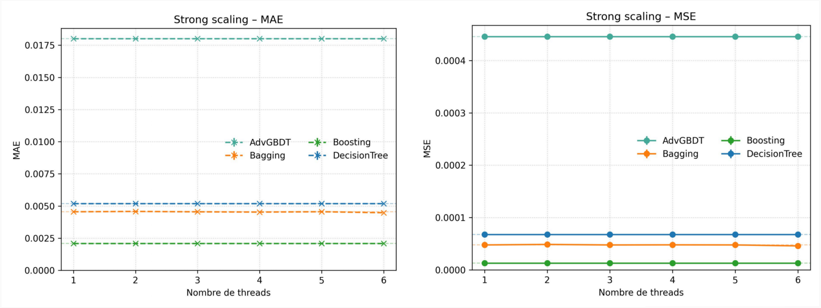


Figure 1: PPN Example - (No Caption)

Plot Example (2)

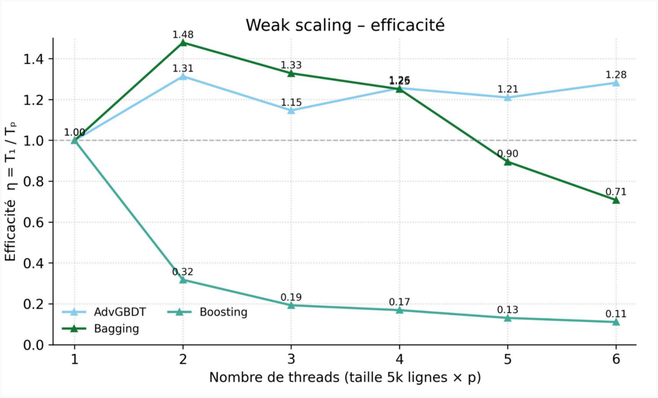


Figure 2: PPN Example - (No Caption)

Plot Example (3)

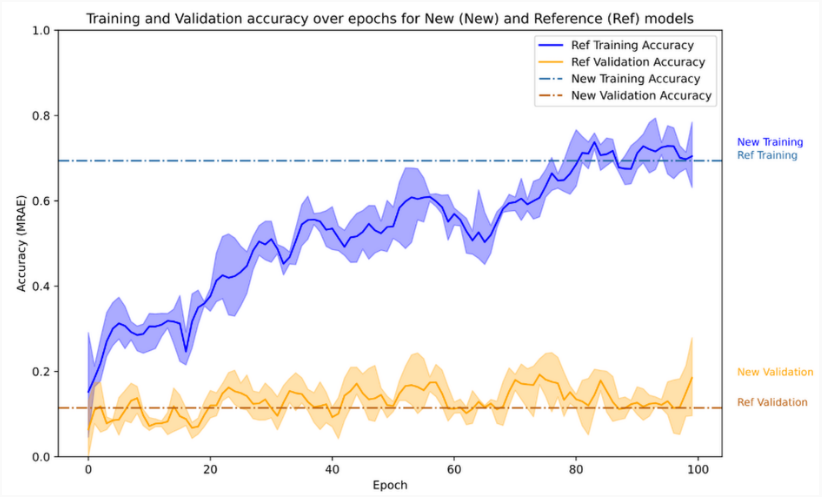


Figure 3: PPN Example - (No Caption)

Plot Example (4)

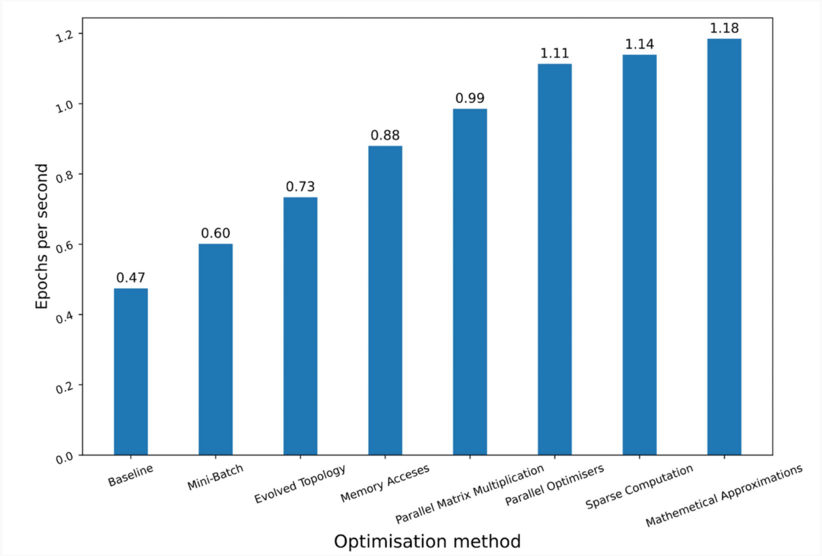


Figure 4: PPN Example - “Récapitulatif des optimisations faites”

Plot Example (5)

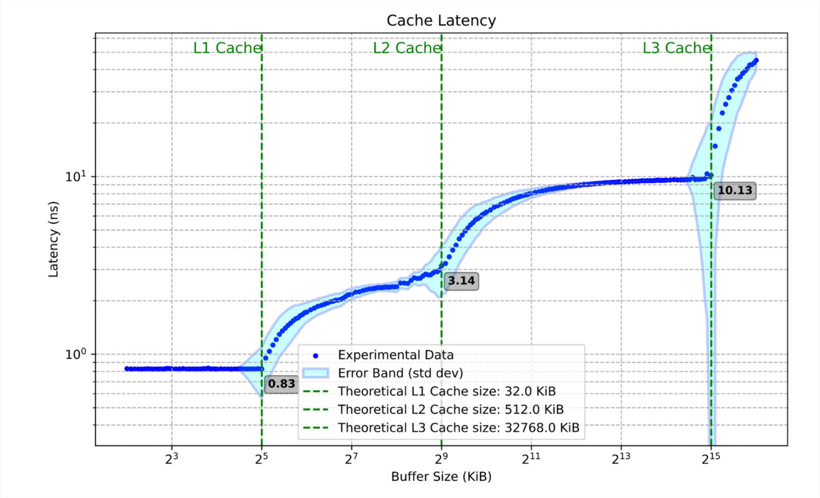


Figure 5: PPN Example - “Nouveau tracé de la latence cache”

Plot Example (6)

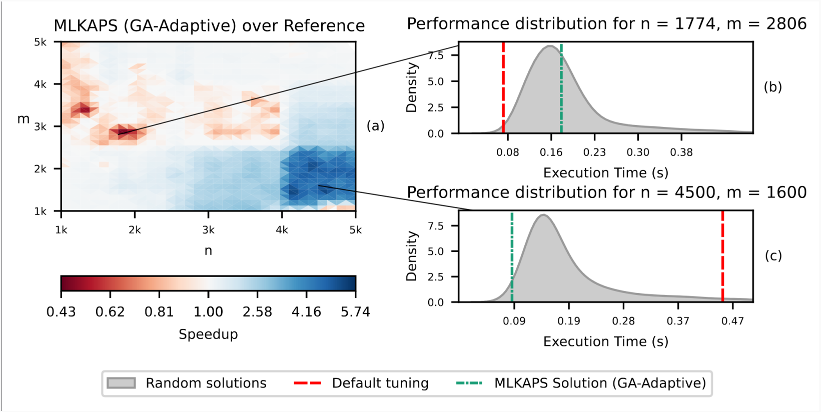


Figure 6: Prof Example - (KNM): (a) Speedup map of GA-Adaptive (7k samples) over the Intel MKL hand-tuning for `dgetrf` (LU), higher is better. (b) Analysis of the slowdown region (performance regression). (c) Analysis of the high speedup region. $3,000$ random solutions were evaluated for each distribution.

Plot Example (7)

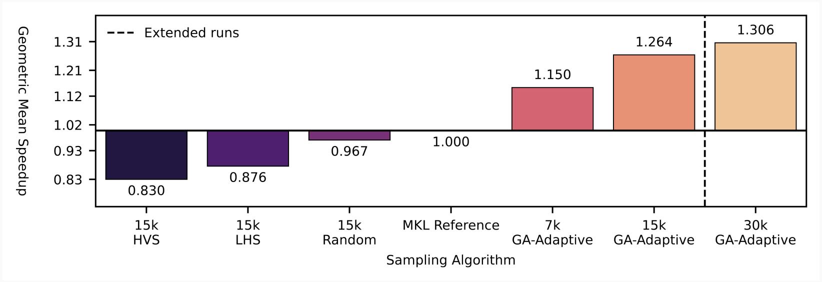


Figure 7: Prof Example - (SPR): Geometric mean Speedup (higher is better) against the MKL reference configuration on `dgetrf` (LU), depending on the sampling algorithm. 46x46 validation grid. 7k/15k/30k denotes the samples count. GA-Adaptive outperforms all other sampling strategies for auto-tuning. With 30k samples it achieves a mean speedup of $\times 1.3$ of the MKL dgetrf kernel.

Plot Example - What makes a good plot

Ask yourself:

- What do I want to communicate ?
- What data do I need ?
- **Is my plot understandable in ~10 seconds ?**
- Is my plot self-contained ?
- Is the context, environment, and methodology clear ?

Plot Example - Summary

HPC is a scientific endeavour; data analysis and plotting are essential.

- Plots drive decisions
- Plots make results trustworthy
- Plots explain complex behaviors

Datasets are large, multi-disciplinary, and often hard to reproduce.

Experimental Methodology

Experimental Methodology - Workflow

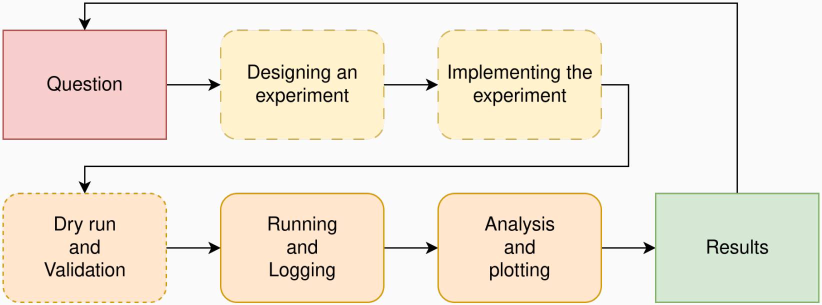


Figure 8: Typical experimental workflow

Statistical significance - Introduction

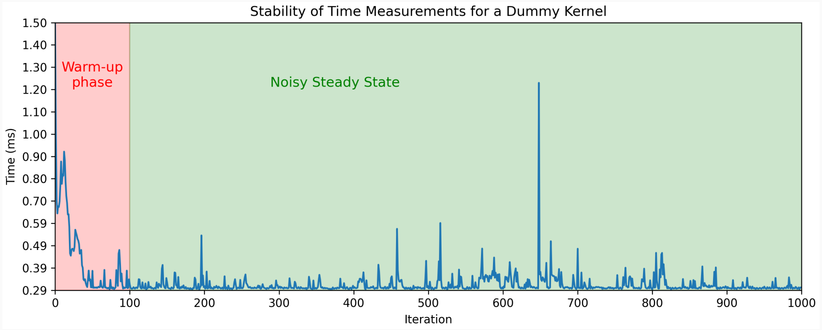
Computers are noisy, complex systems:

- Thread scheduling is non deterministic -> runtime varies between runs.
- Dynamic CPU frequency (Turbo/Boost)
- Systems are heterogeneous (CPU/GPU, dual socket, numa effects, E/P cores)
- Temperature/thermal throttling can alter runtime

How can we make sure our experimental measurements are reliable and conclusive?

Statistical significance - Warm-up effects

Systems need time to reach steady-state:



On a laptop: $\text{Mean} = 0.315\,\text{ms},\ \text{CV} = 13.55\%$

We need “warm-up” iterations to measure stable performance and skip cold caches, page faults, frequency scaling.

Statistical significance - Noise mitigation

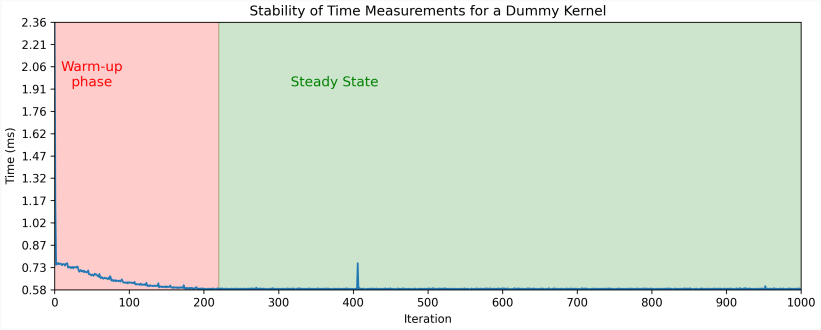
Noise can only be mitigated:

- Stop all other background processes (other users)
- Stabilize CPU Frequency (`sudo cpupower -g performance`)
  - Make sure laptops are plugged to avoid powersaving policies
- Pin threads via `taskset`, `OMP_PLACES` and `OMP_PROC_BIND`
- Consider hyperthreading
- Use stable compute nodes

Meta-repetitions are essential to mitigate noisy measurements.

Statistical significance - Example

Same experiment on a stabilized benchmarking server:



On a laptop: $\text{Mean} = 0.315\,\text{ms},\ \text{CV} = 13.55\%$
Stabilized node: $\text{Mean} = 0.582\,\text{ms},\ \text{CV} = 1.14\%$

Note

Timing on a laptop is always subpar

Statistical significance - Mean, Median, Variance

Single-run measurements are misleading; we need statistics.

- Mean runtime $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$
- Median: less sensitive to outliers than the mean
- Variance/standard deviation: Measure of uncertainty
- Relative metrics are useful: Coefficient of variation ($CV = \frac{\sigma}{\bar{x}} \times 100\%$)

We usually give both the mean and standard deviation when giving performance results. Plots usually show $\bar{x} \pm 1\sigma$ as a shaded region around the mean to represent uncertainty.

Note

Distribution plots can be useful: stable measurements are often close to Gaussian, even if systematic noise may lead to skewed or heavy-tailed distributions.

Statistical significance - Confidence Intervals

How to decide how many repetitions we should perform ?

- Usually, the costlier the kernels, the less meta-repetitions are expected
- Short or really short kernels should have more metas to reduce the influence of noise

Remember that:

$$CI_{0.95} \approx \bar{x} \pm 1.96 \cdot \frac{\sigma}{\sqrt{n}}$$

More repetitions increase confidence, but returns diminish: CI width $\propto \frac{1}{\sqrt{n}}$

Note

Confidence intervals are a bit less common in plots than $\pm 1\sigma$ but can also be used !

Statistical significance - p-score & Hypothesis testing

In HPC, mean/median and variance often suffice, but hypothesis testing can become handy in some contexts.

- Null hypothesis (H_0): GPU and CPU have the same performance for small matrixes
    - Differences in measurements are **only** due to noise
- Alternative hypothesis: CPU is faster for small matrixes
- **p-value** is the probability that H_0 explains a phenomenon.
- If $p < 0.05$, we can safely reject H_0 (Statistically significant difference)

Example: $\bar{x}_{GPU} = 5.0\text{s}$, $\sigma_{GPU} = 0.20$, $\bar{x}_{CPU} = 4.8\text{s}$, $\sigma_{CPU} = 0.4$, Two-sample t-test with 10 samples $p = 0.02$.

The measured differences between CPU and GPU execution time are **statistically significant**.

Experimental Methodology – Reproducibility

Reproducibility is a very hot topic (Reproducibility crisis in science):

- **Data and protocols are first-class citizens**: as important as the plots themselves
- **Transparency** matters: make data, scripts, and parameters accessible
- Enables others to **verify, build on, and trust your results**

Note

Beware of your mindset: your results should be credible and honest before being "good".

"Our results are unstable, we have yet to understand why, this is what we tried" is a completely valid answer

Plotting Tools

Plotting tools - Cheetsheet

Name	Use
pandas	Storing and saving tabular data
numpy	Numerical arrays, manipulating data
matplotlib	Basic 2D plots, full control
seaborn	Statistical plots, higher-level API
logging	Logging experiment progress/results
OpenCV	Image processing, animations/videos
ffmpeg	Generating and encoding videos

Lookup the quick reference plotting gallery in the annex!
Both `matplotlib` and `seaborn` provide extensive online galleries.

[Live Example of the matplotlib gallery https://matplotlib.org/stable/gallery/index.html]

Plotting tools - Matplotlib

Matplotlib is one of the most widely used plotting libraries.
A figure is built hierarchically from nested elements:

```
- Figure (The canvas)
  - (Subfigures)
    - Axes (One or more subplots)
      - Axis (x/y/z scales, ticks, labels)
      - Artists (Lines, markers, text, patches, etc.)
```

- Data is plotted using axis-level functions like `ax.plot`, `ax.histogram`
- Customization occurs at both the Figure and Axes levels
- Complex multi plots layout occur at the Figure level

Plotting tools - Matplotlib

```python
import matplotlib.pyplot as plt

x = [0, 1, 2, 3]
y = [2.8, 5.7, 12.5, 14]

# Create a new figure, single axis
# Size is 8 inches by 8 inches, and constrained layout
fig, ax = plt.subplots(figsize=(8, 8), layout="constrained")

# Plot a simple line
ax.plot(x, y, color="red", label="My Algorithm")

# Customize the axes
ax.set_xlabel("Iteration") # Name of the X axis
ax.set_ylabel("Time (s)") # Name of the y axis
# Title of the plot
ax.set_title("Evolution of Time with the number of iteration")

ax.margins(0, 0) # Remove white spaces around the figure
ax.legend(loc="upper right") # Draw the legend in the upper right
     corner

fig.savefig("my_plot.png", dpi=300) # Higher DPI -> bigger image
plt.close() # End the plot and release resources
```

Plotting tools - Matplotlib (Multi axis)

We can easily have multiple plots on the same figure:

```
nrows = 5, ncols = 1
fig, axs = plt.subplots(5, 1, figsize(8 * ncols, 3 * nrows))

ax = axs[0]
ax.plot()
...

ax = axs[1]
ax.plot()
...

fig.tight_layout() # Alternative to constrained layout
fig.savefig("my_multiplot.png", dpi=300)
```

Each axis is its own plot, with its own legend and artists.

Note

Use the reference (https://matplotlib.org/stable/api/index.html) and gallery (https://matplotlib.org/stable/gallery/index.html) extensively !

Plotting tools - Seaborn

Seaborn is an extension of Matplotlib dedicated to statistical visualization:

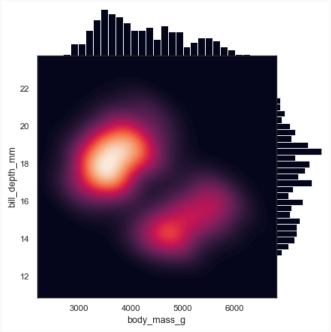


Figure 9: https://seaborn.pydata.org/examples/index.html

It's useful for histograms, bar charts, kdeplots, scatterplots, and is overall a very good companion library.

Plotting tools - Seaborn

```python
import matplotlib.pyplot as plt
import seaborn as sns
import pandas as pd
import numpy as np

df = pd.read_csv(...) # Read the dataframe from somewhere

fig, ax = plt.subplots(figsize=(8, 8), layout="constrained")

# We must pass the axis to plot on as an argument
sns.kdeplot(data=df, x="Time", label="Algorithm", color="red",
    fill=True, ax=ax)

ax.set_title("Distribution of Execution time for the algorithm")
ax.margins(0, 0)
ax.set_xlabel("Time (s)", fontweight="bold")
ax.set_ylabel("Density", fontweight="bold")

ax.set_xticks(np.linspace(df["Time"].min(), df["Time"].max(), 10)
# Format the x axis ticks: `3.25s`
ax.xaxis.set_major_formatter(StrMethodFormatter("{x:.2f}s"))

fig.savefig("my_distribution.png")
```

https://matplotlib.org/stable/gallery/ticks/tick-formatters.html

Profiling

Profiling - Time

gprof

Perf - Introduction

Perf - Performance counters

Profiling - Energy

Perf - Energy

Vtune