

# (R)SE challenges in HPC

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**Abstract**—We discuss some specific software engineering challenges in the field of high-performance computing, and argue that the slow adoption of SE tools and techniques is at least in part caused by the fact that these do not address the HPC challenges ‘out-of-the-box’. By giving some examples of solutions for designing, testing and benchmarking HPC software, we intend to bring software engineering and HPC closer together.

## I. INTRODUCTION

It is a common observation that in the field of high-performance computing (HPC) scientists only slowly adopt new software engineering techniques that are already successful in e.g., web development or commercial applications. This was described from the software engineer’s point of view in [1]. We approach the topic from the HPC engineer’s point of view.

In our opinion, improved training of HPC developers is an important step, but it needs to address specific challenges inherent to HPC software. In contrast to other fields, HPC software always has the design goal of achieving high hardware efficiency, which in turn ensures energy efficiency [2] and makes extreme-scale applications feasible in the first place. In addition to training, tools for programming and testing must be adjusted to work correctly in an HPC environment. In this paper, we present key aspects of software design, testing and performance engineering for HPC software.

## II. CHALLENGES IN HPC SOFTWARE DEVELOPMENT

We identify three key challenges that seem to be invariant with respect to circumstances such as the actual application, hardware or programming skills of the developers.

*First challenge:* The life-cycle of HPC hardware is significantly shorter than that of HPC software, while at the same time software must be tailored to the hardware in order to achieve optimal performance. In the course of a decade the supercomputer hardware evolves dramatically (e.g. from vector processors to clusters of CPUs, from single to multi-core processors, from commodity hardware to graphics or tensor processing units). In contrast, much of the code base in use is at least twenty or thirty years old, and developing e.g. a new aerodynamics code for industrial use may take decades even with a large team and modern software engineering technology.

*Second challenge:* The number of possible code paths grows exponentially in order to provide high performance. A user’s call to a simple basic linear algebra subroutine (BLAS) may trigger any of dozens of implementations, differing in arithmetic (real, complex), precision (half/single/double/quad, or vendor-specific variants thereof), data layout (e.g. row- or column major matrix storage), threading mechanisms or GPU programming model, SIMD hardware (SSE/AVX/ARM/...). This leads to an explosion of combinations of (possibly generated) code paths. In some cases the testing responsibility is with hardware-specific vendor libraries (like the Intel MKL or CUBLAS), but ‘hand-optimized’ code for special purposes must still be tested efficiently and comprehensively.

*Third challenge:* It is difficult to reproduce performance results. Due to the fast pace at which the hardware develops, another user of a code or algorithm may not have a comparable machine in terms of speed, memory, parallelism, or even architecture. Simple and general machine models allow assessing the efficiency of an implementation across platforms, as we will discuss in Section V. They can also ensure that the system’s hardware and software are configured appropriately as even small changes can reduce the performance by a factor of two or more.

## III. DESIGNING HPC SOFTWARE

In order to meet the challenge of the mismatched software/hardware life-cycle it is crucial to achieve *separation of concerns* in HPC applications. The climate scientist who develops a new model component, or the numerical mathematician who develops a new algorithm, cannot port the software to the next few generations of hardware in the life-cycle of the code. Instead, they need robust interfaces through which the application, algorithms and low-level implementations (kernels) are separated. For decades, the libraries BLAS and LAPACK [3] provide a commonly used interface to linear algebra building blocks. However, the choice of the granularity of the *building blocks* as well as their interfaces are *architectural decisions*. In particular, to obtain high efficiency, one needs to optimize the node-level performance as well as the communication. Both of these optimizations often affect the code globally e.g., through the memory-layout and the distribution of data. So new advances such as communication-avoiding algorithms (or better: data-transfer avoiding algorithms, see [4]) cannot always be implemented just under the hood, see [5], [6] for examples.

In [7] we described a layered software architecture for a sparse eigenvalue solver library with applications in quantum physics. The kernel interface we proposed (see also the PHIST software, [8]) allows the algorithms and applications layers to work with multiple backends, among which are large open source libraries optimized for portability (e.g. Trilinos) and hand-optimized hardware-specific ones like GHOST [9]. PHIST provides both unit tests for the backends and performance models for all operations used in its algorithms. That way, a new development on the hardware side can be met by either the extension of an existing implementation or a completely new one, and the new component can be readily tested in terms of correctness and performance. The algorithms and applications layers only have to be modified or extended if new needs arise on their respective level. The significantly larger HPC software project Trilinos [10] takes the approach of offering a large number of interoperable ‘packages’ which may have different life cycles. While this also results in a manageable overall software, it may incur smaller or larger interface adaptations for users from time to time. The package concept is taken to the next level by the xSDK project (<https://xsdk.info>), which aims at gradually improving the software quality and interoperability of a whole landscape of HPC libraries and applications by defining common rules and recommendations.

#### IV. TESTING

Above, we mentioned the potentially large amount of (generated) code that needs to be covered by unit testing. In addition, HPC software often employs multiple parallelization levels at once (e.g., OpenMP for CPU multi-threading, MPI for communication between nodes and CUDA for GPUs). This can lead to functionality that is available but not well-tested. We propose to anticipate typical bugs in HPC codes and to design unit tests specifically to trigger them (similar to *white-box testing* but with multiple different possible implementations in mind). In PHIST, for instance, all basic linear algebra tests are executed for aligned and unaligned memory cases to locate invalid use of SIMD operations. Other typical ‘parallel bugs’ include race conditions and deadlocks. Beyond such HPC-specific tests, one needs to explore the space of available combinations of hardware features with a finite test-matrix by selecting a hopefully representative subset.

A practical problem is that test frameworks typically lack support for MPI applications, as well as for other parallelization techniques such as OpenMP or CUDA. At least MPI support is crucial to run the tests on current supercomputers. An exception is pFUnit [11] for Fortran which supports MPI and OpenMP. For C++ we provide an extended version of GoogleTest with MPI support at [https://github.com/DLR-SC/googletest\\_mpi](https://github.com/DLR-SC/googletest_mpi). It features correct I/O and handling of test results in parallel, as well as collective assertions.

#### V. PERFORMANCE PORTABILITY

In many papers, performance results are reported in terms of ‘scalability’ of a parallel program: either the speed-up

achieved by using more processes to solve the same problem (strong scalability), or the parallel efficiency when increasing the problem size with the number of processes (weak scalability). Such results are not necessarily helpful for comparing the performance on different machines. A better way is to identify the bottleneck in the computation and to report resource utilization with respect to that bottleneck: In the vast majority of HPC codes, the bottleneck is either floating point arithmetic (‘compute bound’ applications), or data movement (‘memory bound’ or ‘communication bound’). This allows estimating the attainable performance by the roofline performance model [12]. With some measurements of cache/memory/network bandwidths and counting of operations and data volumes, one can calculate the achieved performance relative to the (modeled) attainable performance. This relative roofline performance provides a criterion that is independent of the underlying hardware.

Unfortunately, tools cannot easily compute this automatically as it requires high-level insight into the algorithms. For instance, an unfavorable memory access pattern may or may not be avoidable by code or algorithm restructuring. A performance model can be formulated to predict the optimal runtime of the bad access pattern (labelling a good implementation as efficient). Alternatively, a model can predict the runtime of the actual amount of data traffic needed to perform the operation in an ideal setting (highlighting this part of the algorithm as inefficient). We therefore decided to build the roofline model manually into the timing functionality for all basic operations of the PHIST software, giving the user a choice of these two variants (realistic vs. idealized) [7], [8]. When running the same application on two different machines, one can then compare the overall roofline performance, or the performance achieved by individual operations, even for different hardware and/or backends.

#### VI. SUMMARY

In this overview of software engineering challenges specific to HPC, we argued that HPC applications are particularly vulnerable to poor software engineering because their development and use typically outlasts several generations of HPC hardware. Basic functionality needs to be implemented ‘close to the hardware’, so that supporting (combinations of) multiple architectures and programming models leads to additional complexity and to a large amount of (generated) code which has to be tested. And finally, as the hardware develops rapidly, it is difficult to compare performance results on different machines and hardware architectures.

We illustrated some aspects of software design, unit testing and of the portability of performance results with a practical solution from our own field of research, (sparse) linear algebra. The points we would like to highlight are *separation of concerns* when designing the software, *anticipating HPC-specific bugs*, and using *performance models* to validate the efficiency of an implementation across different hardware.

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