An open-source tool-chain for performance analysis

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Abstract Modern supercomputers with multi-core nodes enhanced by accelerators, as well as hybrid programming models, introduce more complexity in modern applications. Efficiently Exploiting all of the available resources requires a complex performance analysis of applications in order to detect time-consuming or idle sections. This paper presents an open-source tool-chain for analyzing the performance of parallel applications. It is composed of a trace generation framework called EZTRACE, a generic interface for writing traces in multipe format called GTG, and a trace visualizer called VITE. These tools cover the main steps of performance analysis – from the instrumentation of applications to the trace analysis – and are designed to maximize the compatibility with other performance analysis tools. Thus, these tools support multiple file formats and are not bound to a particular programming model. The evaluation of these tools show that they provide similar performance compared to other analysis tools, while being generic.

1 Introduction

Numerical simulation has become one of the pillars of science in many domains: numerous research topics now rely on computational simulation for modeling physical phenomenons. The need for simulation in various computer power hungry research

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areas, such as climate modeling, computational fluid dynamics, and astrophysic, has led to designing massively parallel computers that now reach petaflops. Given the cost of such supercomputers, high performance applications are designed to exploit the available computing power to its maximum. During the development of an application, the optimization phase is crucial for improving the efficiency. However, this phase requires extensive understanding of the behavior and the performance of the application. The complexity of supercomputer hardware, due to the use of NUMA architectures or hierarchical caches, as well as the use of various programming models like MPI, OpenMP, MPI+threads, MPI+GPUs and PGAS models, makes it more and more difficult to understand the performance of an application. Due to the complexity of the hardware and software stack, the use of convenient analysis tools is a great help for understanding the performance of an application. Such tools permit the user to follow the behavior of a program and to spot its problematic phases.

This paper describes a complete set of tools designed for performance analysis, from the instrumentation of parallel applications using EZTRACE to the analysis of their execution with VITE. This open-source tool-chain provides a convenient and performant means to understand the behavior of an application.

The remainder of this paper is organized as follows: in Section 2, we present various research related to performance analysis. The design of EZTRACE– our instrumentation framework – is described in Section 3. Section 4 presents the GTG tracing library. Section 5 provides an overview of our trace visualization tool named VITE. The results of experiments conducted on EZTRACE are discussed in Section 6. Finally, in Section 7, we draw a conclusion and introduce future work.

2 Related work

Since the advent of parallel programming and the need for optimized applications, numerous work has been conducted on performance analysis. Tools were designed for tracing the execution of parallel applications in order to understand their behavior. Some of these tools are specific to a particular library – MPE [4] targets MPI applications, POSIX THREAD TOOL [6] aims at applications that use pthreads, OMPTRACE [3] instruments OpenMP applications, ... – Others, such as VAMPIRTRACE [11], TAU [13] or SCALASCA [7], provide multiple modules and thus can track calls to multiple libraries. Instrumenting custom libraries or applications can be achieved with these tools by manually or automatically instrumenting the code.

The format of the trace generated by a tracing tool is usually specific, leading to incompatibility between performance analysis tools. Generic trace formats were designed to meet the needs of several tools. The PAJÉ format [8] permits the user to depict the execution of a program in a generic and hierarchic way. The OPEN TRACE FORMAT [9] (OTF) provides a generic and scalable means of tracing parallel applications more adapted to MPI applications using various communicators.

Exploring a trace file thus requires a tool designed for a particular trace format. For instance, OTF traces can be viewed with VAMPIR [10], TRIVA [12] displays PAJÉ traces, and the files generated with MPE can be visualized with JUMPSHOT [4]. TAU and SCALASCA embed their own trace file viewer. The lack of multiformat trace viewers forces users to switch from one system to another, depending on the tracing tool in use. A complete tool-chain – from the application tracing to the trace analyzer – able to manipulate several trace formats, would allow users to use the most relevant format for each application to analyze.

3 Instrumenting applications with EZTRACE

EZTRACE [14] has been designed to provide a simple way to trace parallel applications. This framework relies on *plugins* in order to offer a generic way to analyze programs; depending on the application to analyze or on the point to focus on, several modules can be loaded. EZTRACE provides pre-defined *plugins* that give the ability to the user to analyze applications that use MPI libraries, OpenMP, or Pthreads. However, user-defined *plugins* can also be loaded in order to analyze application functions or custom libraries.

EZTRACE uses a two-phases mechanism for analyzing performance. During the first phase that occurs while the application is executed, functions are intercepted and events are recorded. After the execution of the application, the *post-mortem* analysis phase is in charge of interpreting the recorded events. This two phase mechanism permits the library to separate the recording of a function call from its interpretation. It thus allows the user to interpret a function call event in different ways depending on the point he/she wants to focus on. It also reduces the overhead of profiling a program; during the execution of the application, the analysis tool should avoid performing time-consuming tasks such as computing statistics or interpreting function calls.

3.1 Tracing the execution of an application

During the execution of the application, EZTRACE intercepts calls to the functions specified by *plugins* and records events for each of them. Depending on the type of functions, EZTRACE uses two different mechanisms for interception. The functions defined in shared libraries can be overriden using LD_PRELOAD: When the EZTRACE library is loaded, it retrieves the addresses of the functions to instrument. When the application calls one of these functions, the version implemented in EZTRACE is called. This function records events and calls the actual function. The LD_PRELOAD mechanism cannot be used for functions defined in the application since there is no symbol resolution. In that case, EZTRACE uses the DYNINST [2] tool for instrumenting the program on the fly. Using DYNINST, EZTRACE modifies the program to record events at the beginning and/or at the end of each function to instrument.

For recording events, EZTRACE relies on the FXT library [5]. Each process being instrumented by EZTRACE generates a trace file using FXT. In order to keep the trace size as compact as possible, FXT records events in a binary format that contains only the minimum amount of information: a timestamp, an *event code* and optional parameters.

3.2 Instrumenting an application

Since EZTRACE uses a two-phases mechanism, plugins are organized in two parts: the description of the functions to instrument, and the interpretation of each function call. During the execution of the application, the first part of the plugin is in charge of recording calls to a set of functions as described in Section 3.1. The second part of the plugin is in charge of adding semantic to the trace. EZTRACE provides plugins for major parallel programming libraries (MPI, OpenMP, PThread, etc) but also allows user-defined plugins designed for custom libraries or applications. For example, the PLASMA linear algebra library [1] is shipped with an EZTRACE plugin.

Fig. 1 Example of function instrumentation using the script language.

```
int submit_jobs(int nb_jobs) BEGIN ADD_VAR("Number of jobs",
     nb_jobs)
CALL_FUNC EVENT("New jobs") END

void do_work() BEGIN RECORD_STATE("Working") END
```

In order to ease the creation of a plugin, we designed a compiler that generates EZTRACE modules from a simple script file. As depicted in Figure 1, such a script consists of a list of functions to instrument and the interpretation of each function. In this example, when the function `submit_jobs` is called, EZTRACE increases the value of a counter, calls the original function, and creates an event. A call to `do_work` is represented as a change of the state in the output trace. This give the possibility to the users to create easily new EZTRACE modules. Since the compiler generates C files, advanced users can tune the created module to fit their needs.

4 Creating trace files with GTG

During the *post mortem* analysis phase, EZTRACE browses the recorded events and interprets them. It can then generate statistics – such as the length of messages, the duration of critical sections, etc. – or create a trace file for visualizing the application behavior. For generating trace files, EZTRACE relies on the Generic Trace

Generator (GTG) library [1]. GTG provides an abstract interface for recording traces. This permits the application to use a single interface for creating traces in multiple formats. Thus, an application can generate PAJÉ traces or OTF files without any modification.

4.1 Overview of GTG

Although trace formats are different, most of them rely on the same structures and provide similar functionalities as it is depicted in Figure 2. A set of hierarchical *containers* (1) represents processing entities such as processes, threads, or GPUs. These containers have *states* (2) that depict events that start at time T_1 and end at time T_2 – the execution of a function, the processing of a computing kernel, a pending communication, etc. – Some *events* (3) (sometimes defined as *markers*) are immediate (*i.e.* $T_1 = T_2$), and can represent the release of a mutex, the submission of a job, etc. Most trace formats also provide a way to track a *counter* (4) such as the total allocated memory, the number of pending jobs or the number of floating point operations per second. In order to symbolize the interaction between containers, trace formats often provide a *link* (5) feature: a couple of *events* that may happen on different *containers*. This permits the viewer tool to represent for example: communications between processes, or signals between threads.

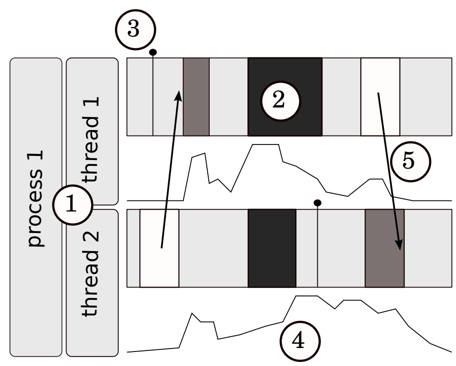


Fig. 2 Features commonly provided by trace formats.

GTG provides a simple interface for manipulating these features. This interface then calls one of the available modules depending on the output trace format.

[1] Available under the CeCILL-C license at http://gtg.gforge.inria.fr/

4.2 Interaction between **GTG** *and* **EZTRACE**

Once EZTRACE is running along with the application, fxt traces are generated. The second part of EZTRACE is based on GTG, and transforms the raw traces to real meaningful traces. First a meaning is added (for example 42 represents an `MPI_Send` request according to the MPI plugin). The semantic can represent links, events, states, etc. The hierarchical structure of the generated trace is PAJÉ like, althought OTF traces can also be generated. The containers can have states (*' This thread is in this function'*), notify events, or count relevant data (number of messages, memory used, number of jobs, etc). This step is based on the plugins (plugins give different meaning to the symbols). Using the EZTRACE convert tool based on GTG, one can add meaning, define containers, and describe what is happening in a function.
Althought Pajé and OTF are both traces format, they have some differences. Thus, adding a meaning to a raw fxt event is the critical part and the event must be interpreted in a way that is conformed to the output format choosen by the user. Otherwise, the traces will not represent the data they should.

5 Analyzing trace files with VITE

The trace files generated by tools such as GTG or VAMPIRTRACE can be parsed for extracting statistics – such as the average message size –, however, understanding the behavior and the performance of an application requires a more convenient tool. In this Section, we present VITE [2] – which stands for *Visual Trace Explorer* –, an open-source multi-format trace visualizer.

5.1 A generic trace visualizer

Originally, the PAJÉ [8] trace visualizer was designed to analyze parallel applications using a simple yet generic trace format. The decline of PAJÉ led students to design a new PAJÉ trace viewer. VITE was designed as a generic trace visualizer, and additional trace formats such as OTF and TAU were added later. To manage multiple formats, VITE relies on a module architecture as depicted in Figure 3.

A set of modules are in charge of parsing traces and filling the generic data structure. VITE implements parsers for several trace formats: OTF, PAJÉ, extended PAJÉ (a multiple files PAJÉ format) and TAU formats. Filling the generic data structure is a critical part of VITE: traces may have millions of events and their processing – storing events, browsing through the event list, finding associated data, etc. – has to be efficient. The last modules are in charge of rendering traces. Such a module uses

[2] freely available at http://vite.gforge.inria.fr/

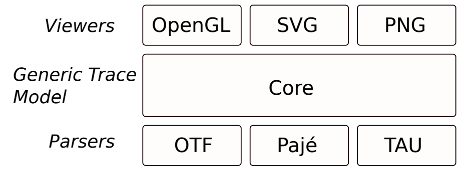
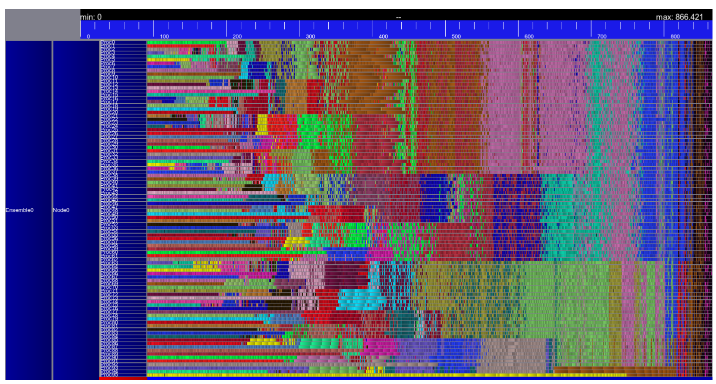


Fig. 3 Modules architecture in VITE.

the data structure to display the trace as requested by the user. A graphical interface based on QT and OpenGL allows for user-friendly browsing of the trace. Additional rendering modules generate SVG or PNG files depicting traces to easily export the results.

Although trace formats are different in their design, most of them provide similar functionalities. VITE implements a generic data structure and manipulates abstract objects representing the different features defined by trace formats. This abstraction permits the developpers to easily implement additional parsers for new trace formats, while rendering traces in a homogeneous way.

5.2 Displaying millions of events



VITE is able to display millions of items. To manage such performances, an efficient data structure and a good rendering is needed. The data structure is based on sorted binary trees, as depicted in Figure 4. Thanks to these trees, any element can be accessed in logarithmic time and unneeded branches of the tree can be avoided.

The binary tree structure is also useful for rendering the trace. In order to avoid creating millions of graphical elements, portions of the trace have to be summarized. VITE uses a resolution parameter for eliminating the events that are too small to be rendered: if a node and his father are too close, then the resolution will not be enough for displaying them, and it is useless to keep on browsing all the nodes between the

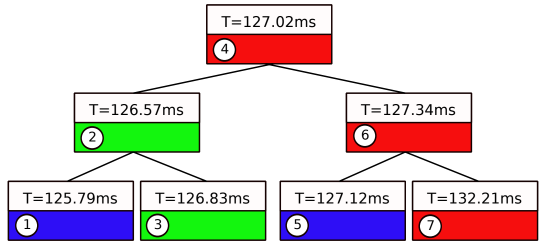


Fig. 4 Example of sorted binary tree representation of events.

two (the subtree of the node on the same side as the father). For example, when rendering the binary tree depicted in Figure 4 with a resolution of 1 ms, VITE browses event *# 4*. It then handles *# 2*. Since the interval between events *# 2* and *# 4* is lower than the resolution ($T_{\#4} - T_{\#2} < 1ms$), event *# 3* is not taken into account. Event *# 1* is then handled normally. Then, VITE processes event *# 6*. Event *# 5* is skipped since it is beneath the resolution ($T_{\#6} - T_{\#4} < 1ms$) and event *# 7* is handled normally. As a result, the number of elements to display, as well as the number of nodes to browse, is limited increasing the rendering performance. If the user zooms in, the resolution decreases and the same algorithm is used.

The rendering is also critical; OpenGL has been chosen after benchmarking several solutions based on Qt, GTK, SDL, GNUStep and JAVA. Despite the fact that Qt and GTK could provide a better and easier interaction with the trace, the OpenGL engine, with our own mouse placement detection, appeared to be the most scalable solution. Moreover, on some machines, OpenGL can benefit from hardware optimization with the GPU.

6 Evaluation

When analyzing the performance of parallel applications that generate millions of events, the performance of the analysis tool is important. The overhead of the instrumentation should be as low as possible, and the visualization tool should allow a smooth browsing of the resulting trace. In this Section, we assess the performance of EZTRACE. We evaluate the raw performance of the instrumentation mechanisms used in EZTRACE on a synthetic benchmark as well as on application kernels.

The results of this evaluation were obtained on the CLUSTER0 platform. It is composed of 32 nodes, each being equipped with two 2.2 GHz dual-core OPTERON (2214HE) CPUs featuring 4 GB of memory. The nodes are running Linux 2.6.32 and are interconnected through MYRINET MYRI-10G NICs. We compare EZTRACE with VAMPIRTRACE in its 5.9 version.

6.1 Overhead of trace collection

In order to evaluate the raw overhead of program instrumentation, we use an MPI ping pong program. We measure the latency obtained for 16-bytes messages. We instrument this program using the automatic (*i.e.* using LD_PRELOAD) and manual (*i.e.* using DYNINST) mechanisms described in Section 3.1, then we compare the overhead of using EZTRACE or VAMPIRTRACE to the performance obtained without instrumentation. For VAMPIRTRACE, the automatic instrumentation is obtained by using its MPI module. The manual instrumentation is obtained by inserting call to VT_USER_START and VT_USER_END in the application.

Table 1 shows the results we obtained. Using VAMPIRTRACE automatic instrumentation degrades the latency by 1.1 μs while the manual instrumentation causes an overhead of 700 ns. The difference is due to the fact that VAMPIRTRACE generates events at the entry and the exit of functions in both instrumentations, but it also generates a *SendMessage* or *ReceiveMessage* event when the MPI module is selected.

Instrumenting the application with EZTRACE causes an overhead of 700 ns for both mechanisms. This is because EZTRACE records events at the entry and the exit of functions for both manual and automatic modes. The *SendMessage* and *ReceiveMessage* events are generated during the *post mortem* phase.

Table 1 Results of the 16-bytes latency test

Method	Open MPI	VampirTrace	EZTrace
Automatic	4.99 μs	6.12 μs	5.68 μs
Manual	4.99 μs	5.71 μs	5.67 μs

6.2 NAS parallel benchmarks

In order to evaluate the overhead of EZTRACE on more realistic computing kernels, we also measure its performance for NAS application kernels. The experiment was carried out with 4 computing processes for Class A and 32 processes (or 36 for BT and SP that require a square number of processes) for Class B. We instrument MPI functions of these kernels with EZTRACE and VAMPIRTRACE automatic modules.

Table 2 summarizes the results we obtained. Since EZTRACE *post mortem* phase crashes for the LU kernel for Class B, the number of events in the resulting OTF trace is not reported. The results show that instrumenting these kernels with EZTRACE or VAMPIRTRACE does not significantly affect the performance: variation of the execution time is less than 2 %. This experiments also show that intensive event recording kernels – such as MG or CG for Class B – do not suffer from the overhead of the instrumentation.

Table 2 NAS Parallel Benchmark performance for Class A and B

Kernel	Class	# Processes	OpenMPI	VampirTrace		EZTrace		# Events / s
				Execution (s)	Overhead	Execution (s)	Overhead	
BT	A	4	70.57	70.58	0.01 %	70.39	-0.26 %	825
CG	A	4	2.64	2.68	1.52 %	2.68	1.52 %	12 546
EP	A	4	9.61	9.69	0.83 %	9.72	1.14 %	5
FT	A	4	6.63	6.67	0.55 %	6.62	-0.20 %	22
IS	A	4	0.63	0.64	2.13 %	0.62	-1.06 %	482
LU	A	4	42.08	42.15	0.17 %	41.39	-1.64 %	12 282
MG	A	4	5.04	5.06	0.46 %	5.07	0.66 %	2978
SP	A	4	166.25	165.94	-0.18 %	166.32	0.04 %	696
BT	B	36	26.08	25.83	-0.97 %	26.37	1.10 %	59 350
CG	B	32	16.29	16.46	1.02 %	16.60	1.88 %	192 667
EP	B	32	4.81	4.79	-0.42 %	4.76	-1.04 %	81
FT	B	32	11.76	11.61	-1.30 %	11.55	-1.81 %	255
IS	B	32	0.97	0.96	-1.03 %	0.96	-1.03 %	2 580
LU	B	32	33.75	34.11	1.07 %	33.67	-0.24 %	–
MG	B	32	2.14	2.16	0.78 %	2.13	-0.62 %	215 515
SP	B	36	51.18	51.98	1.57 %	52.07	1.75 %	59 922

7 Conclusion and future work

Programming a parallel application that efficiently exploits a supercomputer becomes more and more tedious due to the increasing complexity of hardware – multicore processors, NUMA architectures, GPGPUs, etc. – and the use of hybrid programming models that mix MPI, OpenMP or CUDA. Tuning such an application requires the programmer to precisely understand its behavior.

We proposed in this paper an open-source tool-chain for analyzing the performance of modern parallel applications. This software suite is composed of EZTRACE – a generic framework for instrumenting applications –, GTG – a tool for generating traces in multiple formats –, and VITE – a trace visualizer that supports several trace formats –. These tools were designed to provide an open-source alternative to other performance analysis tools, while allowing interoperability with other tools such as Vampir or TAU. The evaluation shows that this genericity does not imply extra overheads since EZTRACE provides similar performance when compared to VAMPIRTRACE.

In the future, we plan to study more precisely the performance of the whole software suite and to improve it. Additional modules are to be developped in EZTRACE in order to allow the analysis of programs running CUDA or OpenCL. We also plan to improve EZTRACE performance analysis capabilities so that it can detect programming or runtime issues such as network congestion or insufficient overlap of communication and computation. Future work concerning GTG includes the support for other trace formats – such as TAU – and enhancing the API. We also plan to merge VITE and TRIVA [12] projects. TRIVA is based on PAJÉ software and provides new ways of displaying information such as treemaps, or network graphs that will benefit to ViTE. On the other side, TRIVA will benefit from the multi-format parser and from the OpenGL display.

References

1. Agullo, E., Demmel, J., Dongarra, J., Hadri, B., Kurzak, J., Langou, J., Ltaief, H., Luszczek, P., Tomov, S.: Numerical linear algebra on emerging architectures: The plasma and magma projects. In: Journal of Physics: Conference Series, vol. 180, p. 012037. IOP Publishing (2009)
2. Buck, B., Hollingsworth, J.: An API for runtime code patching. International Journal of High Performance Computing Applications **14**(4), 317–329 (2000)
3. Caubet, J., Gimenez, J., Labarta, J., DeRose, L., Vetter, J.: A dynamic tracing mechanism for performance analysis of OpenMP applications. OpenMP Shared Memory Parallel Programming pp. 53–67 (2001)
4. Chan, A., Gropp, W., Lusk, E.: An efficient format for nearly constant-time access to arbitrary time intervals in large trace files. Scientific Programming **16**(2-3), 155–165 (2008)
5. Danjean, V., Namyst, R., Wacrenier, P.: An efficient multi-level trace toolkit for multi-threaded applications. Euro-Par 2005 Parallel Processing pp. 166–175 (2005)
6. Decugis, S., Reix, T.: NPTL Stabilization Project. In: Linux Symposium, vol. 2, p. 111 (2005)
7. Geimer, M., Wolf, F., Wylie, B., Ábrahám, E., Becker, D., Mohr, B.: The scalasca performance toolset architecture. Concurrency and Computation: Practice and Experience **22**(6), 702–719 (2010)
8. de Kergommeaux, J., de Oliveira Stein, B.: Pajé: an extensible environment for visualizing multi-threaded programs executions. In: Euro-Par 2000 Parallel Processing, pp. 133–140. Springer (2000)
9. Knüpfer, A., Brendel, R., Brunst, H., Mix, H., Nagel, W.: Introducing the open trace format (OTF). Computational Science–ICCS 2006 pp. 526–533 (2006)
10. Knüpfer, A., Brunst, H., Doleschal, J., Jurenz, M., Lieber, M., Mickler, H., Müller, M., Nagel, W.: The Vampir Performance Analysis Tool-Set. Tools for High Performance Computing pp. 139–155 (2008)
11. Muller, M., Knüpfer, A., Jurenz, M., Lieber, M., Brunst, H., Mix, H., Nagel, W.: Developing scalable applications with Vampir, VampirServer and VampirTrace. Proceedings of the Minisymposium on Scalability and Usability of HPC Programming Tools at PARCO (2007)
12. Schnorr, L.M., Huard, G., Navaux, P.O.: Triva: Interactive 3d visualization for performance analysis of parallel applications. Future Generation Computer Systems **26**(3), 348 – 358 (2010)
13. Shende, S., Malony, A.: The TAU parallel performance system. International Journal of High Performance Computing Applications **20**(2), 287 (2006)
14. Trahay, F., Rue, F., Faverge, M., Ishikawa, Y., Namyst, R., Dongarra, J.: EZTrace: a generic framework for performance analysis. In: IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid). Newport Beach, CA (2011)