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Tracing methodologies and tools for Artificial Intelligence and Data Mining Java applications

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"Successful people keep moving.
They make mistakes, but they don't quit."
— Conrad Hilton

Abstract

Supercomputing and Artificial Intelligence have been behind the scenes of many recent discoveries. From an implementation point of view, nowadays they use parallel and distributed approaches, that best fit the modern hardware architecture. In this context, the Java programming language plays a marginal role. However, Java is still in high demand, it is employed in AI and runs effectively on supercomputers. Even if a smaller set of programmers use it for HPC (High Performance Computing) applications, its influence in the AI world is not negligible and it deserves a larger attention to the tools that support its development in such environment.

An important tool to improve HPC programs is Performance Analysis, that is concerned with achieving efficient utilisation of system resources. A common technique is to collect trace data and then analyse it for possible causes of poor performance. The Performance Tools department of the Barcelona Supercomputing Center (BSC), is in charge of developing this kind of tools, and this thesis has been carried out as an intern in this department. For this reason the base of the work is going to be on the two main tools developed there: Extrae and Paraver. The former is the program needed to extract information, while the second one is used to show them.

The state of the art of Extrae's instrumentation for Java is poorly implemented. Out of some basic features to trace basic thread events, using the instrumentation of pthreads (on which all Java threads are mapped), it does not give much valuable information. A study on the state of the art is covered in chapter 2.

Since Extrae is implemented in C, generating probes and wrappers would not be an issue for other C-implemented programs, and it obviously results to be harder to do for Java programs. For this reason, in chapter 3 there is an overview of the approaches that can be used to generate the traces for a Java program.

The approach that is then developed is going to be based on an event-driven platform offered by the JVM (the JVM TI), united to the extension for the Java language that implement aspect-oriented programming paradigm (AspectJ). The development of this platform follows in chapter 4 and chapter 5, and it will be applied on two real frameworks for Java (Hadoop and Spark) in chapter 6, where also discussions on the whole work of the thesis can be found.

The scope of this thesis has not been on delivering a final product, rather than defining some methodologies that can be employed to instrument any kind of Java framework.

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Acronyms

AI

    Artificial Intelligence

AOP

    Aspect Oriented Programming

API

    Application Programming Interface

BSC

    Barcelona Supercomputing Center

HPC

    High Performance Computing

JNI

    Java Native Interface

JVM

    Java Virtual Machine

JVM TI

    Java Virtual Machine Tool Interface

Chapter 1

Introduction

1.1 Context: High Performance Computing, Artificial Intelligence and Java

Supercomputing and Artificial Intelligence are among the most important outcomes of the last decades. Both of them have been behind the scenes of many recent discoveries, correctly credited to other classes of instrumentation (e.g. the Hubble telescope), but that required supercomputing and AI as the enabling tools for large datasets processing—usually referred to as "Big Data" [1] [2].
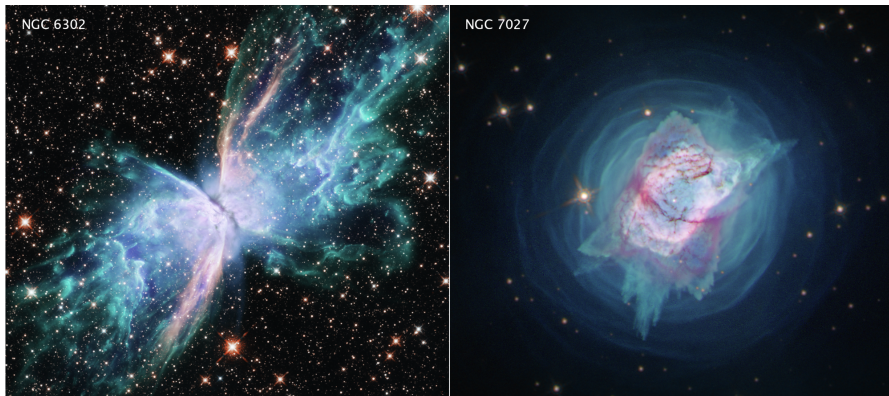
Figure 1.1: Two Planetary Nebulas photographed by the Hubble Telescope [3]

AI applications, from Deep Learning to Data Mining, going through Neural Networks and Clustering algorithms, together with most of the applications in general,

have been switching from a sequential paradigm to parallel and distributed approaches, that best fit the new hardware. The High Performance Computing (HPC) discipline is at the heart of these developments.

HPC is a field of endeavor that relates to all facets of technology, methodology, and application associated with achieving the greatest computing capability possible at any point in time and technology. The action of performing an application on a supercomputer is widely termed "supercomputing" and is synonymous with HPC (T. Sterling *et al* [1, p. 3]).

In this context, the Java programming language plays a marginal role. Languages such as R and Python are much more common when manipulation of Big Data and statistic analysis are the primary goals [4]. However, Java is still in high demand, it is employed in AI and runs effectively on supercomputers. Even if a smaller set of programmers use it for HPC applications, its influence in the AI world is not negligible and it deserves a larger attention to the tools that support its development in such environment.

1.1.1 Java-powered AI and Data Mining

The high and always increasing demand of AI features has affected almost all the programming languages. Research institutions and companies started to invest on AI and Machine Learning [5]. Java, as one of the most common languages, got a bunch of new libraries to enable the developers to access this various world, made of statistics and algorithms. Among all the frameworks for AI, Machine Learning and Data Mining, the ones listed below are probably the most common ones employed with Java. Worthy to be in a resume and capable of figuring in the skills requirement of some tech careers.

Weka The Waikato Environment for Knowledge Analysis (Weka) is an open source software developed at the University of Waikato, in New Zealand. The Weka workbench is a collection of machine learning algorithms and data preprocessing tools, providing a Java library and a graphical User Interface to train and validate data models. It is among the most common Machine Learning frameworks for Java, since it was one of the first ones and it is still maintained [6].

Apache Spark MLlib Apache Spark is an open-source distributed general-purpose cluster-computing framework. Spark provides an interface for programming entire clusters with implicit data parallelism and fault tolerance. Spark Core provides distributed task dispatching, scheduling, and basic I/O functionalities, exposed through an application programming interface (for Java, Python, Scala, and R) centered on the Resilient Distributed Dataset (RDD) abstraction. RDD is

a read-only multiset of data items distributed over a cluster of machines, that is maintained in a fault-tolerant way [7]. Spark MLlib is a distributed machine-learning framework on top of Spark Core that implements many machine learning and statistical algorithms, simplifying large scale machine learning pipelines [8].

Apache Mahout Apache Mahout is a distributed linear algebra framework, written in Java and Scala, whose architecture is built atop a scalable distributed platform. Although Apache Spark is the recommended one, Mahout supports multiple distributed back-ends. The framework features console interface and Java API, that give access to scalable algorithms for clustering, classification, and collaborative filtering [9].

1.1.2   Distributed Java in HPC

The above frameworks are not thought for an HPC environment. The standard implementation of Weka, for example, is designed to run on standard machines (like PCs, laptops or small servers), with most of the algorithms implemented sequentially. This makes it difficult to gain advantage of a strongly parallel architecture like a supercomputer. Spark and Mahout, instead, run both on a distributed platform, which means that they're designed to run on a cluster of different machines instead of a unique system. Java is indeed perfectly suitable to work on a distributed environment, usually using frameworks like MapReduce[1], whose most common implementation is Apache Hadoop, written in Java.

Spark has its own core that work in a similar fashion, Mahout runs on a distributed backend and Weka too can go distributed with some packages, running on frameworks such as Spark or Hadoop [11]. All of them rely directly or indirectly on the map-reduce framework.

Although a supercomputer and a distributed environment, made of nodes connected over a network, are similar from the physical perspective, they're much different when speaking about logic organization. Nevertheless, a distributed system can be deployed on a supercomputer, by keeping the logic organization and taking advantage of its computational power. Such emulated environment can be reached with the use of software containers.

Software containers are a form of OS-level virtualization introduced by Docker. Even if an emulated distributed system can be made of Docker containers, the BSC

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[1]MapReduce is a programming model for processing big data sets with a parallel, distributed algorithm on a cluster. A MapReduce program is composed of a map procedure, which performs filtering and sorting, and a reduce method, which performs a summary operation [10].
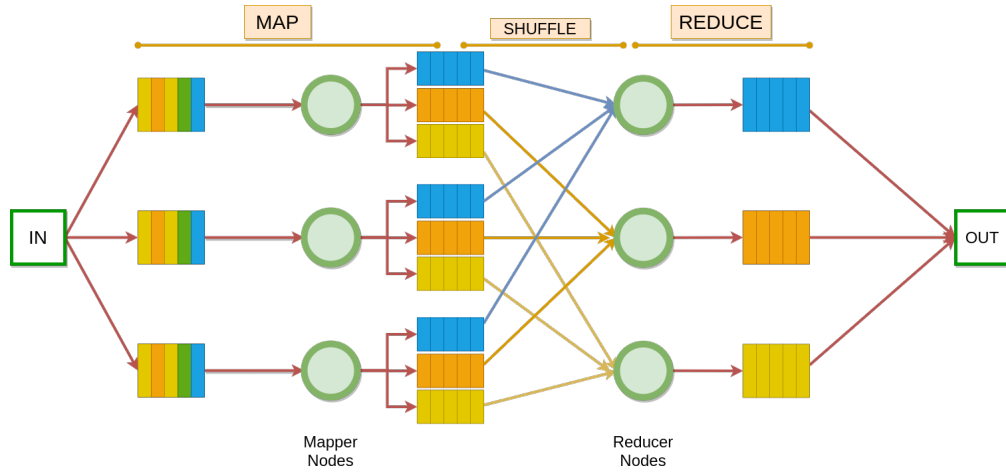
Figure 1.2: How the map-reduce framework works. The nodes can be virtualized using containers.

choice for MareNostrum is Singularity, another type of software containers created as an alternative to Docker for Clusters HPC environments.

Singularity enables users to have full control of their environment. Singularity containers can be used to package entire scientific workflows, software and libraries, and even data [12]. Distributed applications based on Hadoop or Spark can run on supercomputers, by using virtualized clusters made of Singularity containers.

1.1.3 Performance analysis

Quoting prof. Jesus Labarta, one of my professors at the UPC, «measurement techniques are "enablers of science". They are present everywhere, and so they are in Computer Science. In the specific case of HPC, they are represented by the performance analysis tools.»

Parallel program performance analysis and tuning is concerned with achieving efficient utilisation of system resources. One common technique is to collect trace data and then analyse it for possible causes of poor performance. The objective is to gather insights, both qualitative and quantitative, in order to increase predictability, build confidence and properly suggest improvements in the software [13].

A great way to describe the observed behaviour is through performance models, which take in consideration multiple model factors based on specific metrics (load balance, communication efficiency, etc.), making it easier to understand where to act.

1.2 MareNostrum Tools Environment

The work in the present thesis is carried out as an intern at the Barcelona Supercomputing Center (BSC), that has one of the most powerful supercomputers in the world. It is situated right next to the Campus North of the UPC.

The BSC supercomputer is called MareNostrum (Figure 1.3), and it is at its 4th version. With 6,470.8 TFlop/s of max performance, at the time of writing the MareNostrum occupies the 30th position among the most powerful supercomputers in the world, according to the top500 list [14]. It has 165,888 cores, divided on 3,456 nodes, and counts more than 300 TB of memory [15].

Figure 1.3: MareNostrum 4 [15]

The MareNostrum software environment is based on the SUSE Linux Enterprise Server Operating System. There are several available modules ready to be loaded, and many of them are developed within the BSC research departments. Among these modules, we find the performance analysis tools developed at the Performance Tools Department of the BSC: Extrae and Paraver.

1.2.1 Paraver

Paraver is developed to visually inspect the behaviour of an application and then to perform detailed quantitative analysis. It has a clear and modular structure, which gives to the user expressive power and flexibility.

The Paraver trace format has no semantics. Thanks to that, supporting new performance data or new programming models requires only capturing such data

in a Paraver trace. Moreover, the metrics are not hardwired on the tool, but programmed. To compute them, the tool offers a large set of time functions, a filter module, and a mechanism to combine two time lines.

Paraver is not tied to any programming model, as long as the model used can be mapped in the three levels of parallelism expressed in the Paraver trace [16].
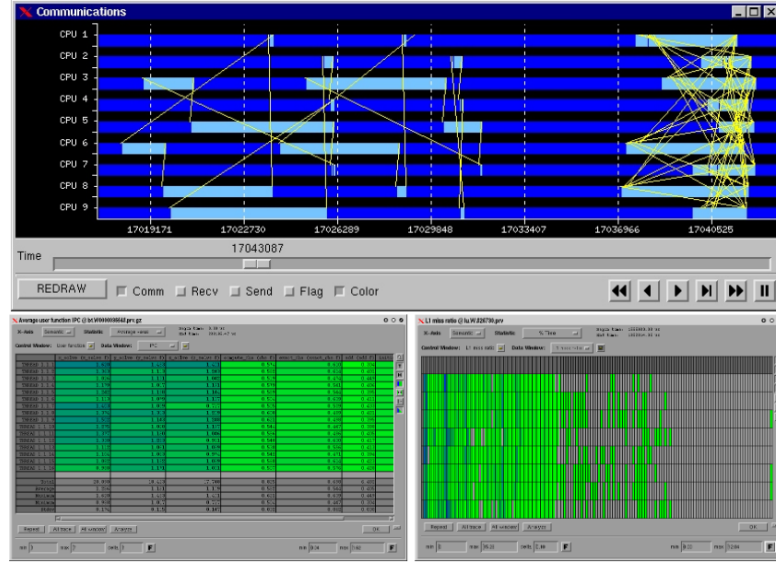
Figure 1.4: Example of traces analysis using Paraver, taken from the BSC website [16]

A Paraver trace file has three types of records: state, event and communication. The state is a record associated to a thread for a specific time interval (running, idle, synchronization, communicating, etc.). The event record is a punctual event that happen on one object, encoded in two integers (type and value). Finally, the communication event relates two objects in two points in time, representing a pair of events in two different threads and a relationship between the event happening in the first thread and the second [17].

The Paraver trace file is a set of three textual files containing the application activity (.prv), the labels associated to the numerical values (.pcf) and the resource usage (.row). Currently, there are several ways to generate Paraver trace-files, like Extrae, Dimemas or other Translators (Figure 1.5) [18]. The tool on which this thesis will focus is Extrae, the core of the instrumentation package developed at the BSC.
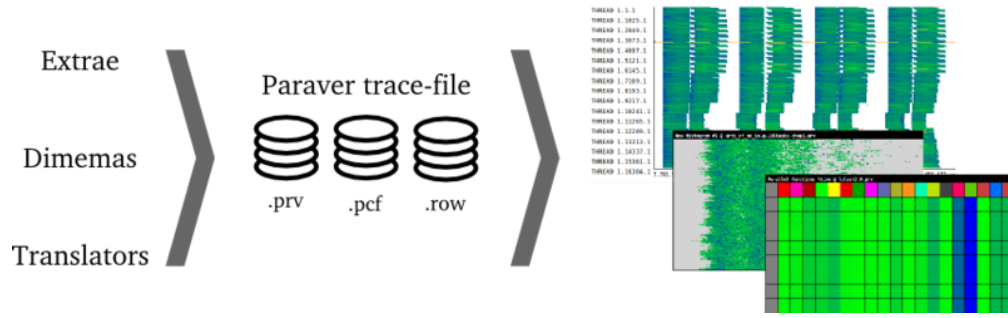
Figure 1.5: Paraver traces generation, taken from the BSC website [19]

1.2.2 Extrae

Extrae is a tool that uses different interposition mechanisms to inject probes into the target application, in order to gather information regarding the application behaviour and performance. It uses different interposition mechanisms to inject the probes, and generates trace-files for an analysis carried after the termination of the program [20].

The most common interposition mechanism consists in using the Linker Preload, that expects to set the `LD_PRELOAD` environment variable to the path of the Extrae tracing library before executing the target program. In this way, if the pre-loaded library contains the same symbols of other libraries loaded later, it can implement some wrappers for the functions valuable to get data from. This is what Extrae does for most of the instrumented programming models.

Another mechanism consists in manually inserting some probes. On top of the instrumented frameworks, Extrae provides an API which gives the user the possibility to manually instrument the application and emit its own events.

Extrae is subjected to different settings, configured through an XML file specified in the `EXTRAE_CONFIG_FILE` environment variable. These settings have the control on almost everything in the instrumentation process. They can enable the instrumentation of some libraries instead of others, the hardware counters, the sampling mode, etc. The tracefiles generated by Extrae are formatted to comply with the Paraver trace format.

Extrae supports different programming models (like MPI, OpenMP, CUDA, etc.) and also basic threads instrumentation and events tracing in Python, Java and `C/C++` (instrumenting the pthread library, in addition to the above mentioned programming models).

The instrumentation for Java, which is the main focus for this thesis, is poorly

implemented. It supports just a basic thread instrumentation, by tracing only the Running state, the Exception event and the Garbage Collection event. The features currently implemented for Java instrumentation are explained in chapter 2.

1.3 Problem Statement and Goal

At the BSC, tracing a Java program is something that has not been given much attention. In the BSC performance tools, Java is poorly instrumented, relies on just few events that do not give enough valuable information on what the program does and how it is improvable.

The contributions of this work aim to:

- Design and implement a Java instrumentation platform, on top of one of the BSC performance tools: Extrae;

- Find some patterns and methodologies that can help analysing Java applications in an HPC environment;

- Doing so, with keeping a focus on the AI frameworks, which represent a large portion of the Java applications that typically run on supercomputers.

Since I developed this thesis as an intern at the Barcelona Supercomputing Center (BSC), the starting basis for the work will be the BSC performance tools. The interest for the company—and so my job as an intern—was to improve such tools (Extrae, mainly) and to gain the right experience in analyzing the typical HPC applications implemented in Java.

In order to do so, the thesis will be developed starting from an analysis of the state of the art of Extrae for Java (chapter 2), by instrumenting an example multi-threaded program. It follows a discussion about the different possibilities of instrumentation methodologies (chapter 3), before actually implementing a solution that tries to trace the Java threads and related events (chapter 4 and chapter 5), in order to get some traces detailed enough to properly study the behaviour of an application.

Finally, the platform is tested against two distributed frameworks: Hadoop and Spark. The study ends with a discussion of the results (chapter 6) and a conclusion (chapter 7), which wrap everything up and give a sense to what has been done and what can be improved.

1.4 Materials and Methods

If not specified, all the executions reported in this thesis ran on a Dell XPS15 9570, with an Intel i7-8750H CPU at 2.20GHz and 32GB of DDR4 RAM. The programming tools employed in the work have been the following:

- Visual Studio Code for all the `C/C++` code

- Jetbrains IDEA IntelliJ for all the Java/AspectJ code

- Docker to virtualize the OS and the tools environment

- GitHub to store all the code and manage Extrae's pull requests and versioning

All the examples are easily reproducible thanks to the virtualization offered by the Docker image. The image is based on OpenSUSE, provides the BSC tools (Extrae and Paraver) and all the other dependencies (AspectJ, Java, etc.) are installed and ready to be used. The reason behind choosing OpenSUSE is because of the MareNostrum 4 Operating System (SUSE Linux Enterprise Server), of which OpenSUSE—being its free version—is the most similar OS that could be virtualized with a Docker image.

An explanation of the usage of the environment, including the steps to build and setup the image, as well as the instructions on how to run the examples, is present in appendix A.

Chapter 2

Extrae for JAVA: State of the Art

This chapter will go through the state of the art of Extrae's instrumentation for Java. It is not totally absent, but its tracing capabilities are currently poorly implemented. The discovery of the available features will be carried out by looking at one at the Extrae's Java example, provided in the Extrae package, which calculates the π number with a parallel algorithm. By analyzing it, this chapter will cover all the aspects of how Extrae traces the Java threads: how it gathers the data and spot the events, how it is launched and what are the experimental features that were added. Additionally, the generated traces will be analyzed in order to understand what events are missing.

2.1 The example program

The program that is going to be analyzed is a simple algorithm to calculate π. It does so 5 times: the first time with a sequential algorithm, the other four with a parallel implementation, respectively with 1, 2, 4 and 8 threads.

The main class is shown in Code 2.1[1]. A scheme of the expected behaviour is reported in Figure 2.1.

Code 2.1: PiExample.java

```java
public class PiExample
{
  public static void main (String [] args)
  {
    PiSerial pis = new PiSerial (steps);
    pis.calculate ();

    PiThreaded pit1 = new PiThreaded (steps, 1);
    pit1.calculate ();

    PiThreaded pit2 = new PiThreaded (steps, 2);
    pit2.calculate ();

    PiThreaded pit4 = new PiThreaded (steps, 4);
    pit4.calculate ();

    PiThreaded pit8 = new PiThreaded (steps, 8);
    pit8.calculate ();
  }
}
```
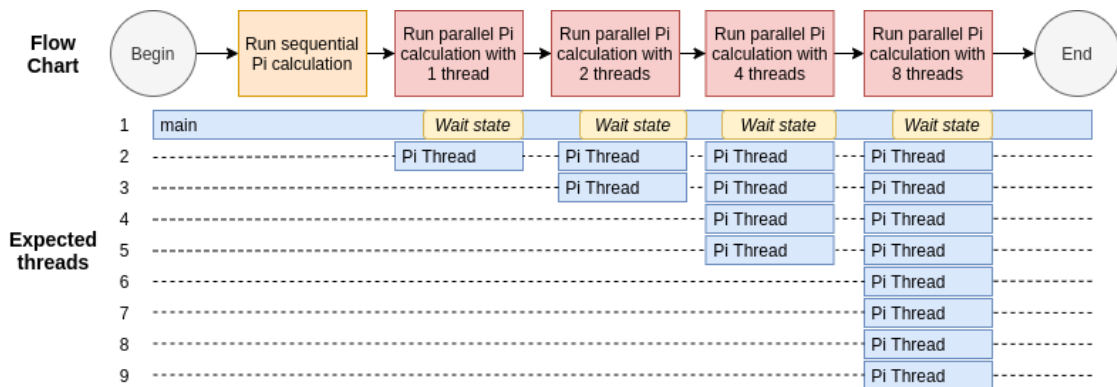

Figure 2.1: PiExample flow chart and expected threads behaviour

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[1]The real Extrae's example contains some time measurements and print messages. Here just the main instructions are reported for brevity.

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The `PiThreaded` class (Code 2.2) is responsible to create and run the threads.

Code 2.2: PiThreaded.java

```java
public class PiThreaded
{
  long m_n;
  double m_h;
  Vector<PiThread> m_threads;

  public PiThreaded (long n, int nthreads)
  {
    m_n = n;
    m_h = 1.0 / (double) n;

    m_threads = new Vector<PiThread>(nthreads);
    for (long i = 0; i < nthreads; i++) {
      m_threads.addElement (
        new PiThread (m_h,
          (n/nthreads)*i,
          (n/nthreads)*(i+1)-1)
      );
    }
  }

  public void calculate ()
  {
    /* Let the threads run */
    for (int i = 0; i < m_threads.size (); i++)
      (m_threads.get(i)).start ();

    /* Wait for their work */
    for (int i = 0; i < m_threads.size (); i++) {
      m_threads.get(i).join ();
    }
  }

  public double result ()
  {
    double res = 0.0;
    for (int i = 0; i < m_threads.size (); i++) {
      /* reduce the value to result */
      res += (m_threads.get(i)).result ();
    }
    return res;
  }
}
```

The classes `PiThread` and `PiSerial`, here omitted for brevity, are both responsible for the actual calculation, but the former extends Java's `Thread` class.

2.2   Generate the traces

Generating the traces for a Java program is done using a launcher script installed by Extrae, named `extraej`. Assuming to use the Extrae XML file contained in the examples, and assuming to have the Java class to test (named `PiExample` in this case) in the Class Path[2], the following command will launch the program and generate the traces:

EXTRAE_CONFIG_FILE=extrae.xml extraej -- PiExample

This command will generate a file called `PiExample.prv` (the name is specified in the `extrae.xml` file). By analyzing the file using Paraver, the result is shown in Figure 2.2. As it can be seen, there are not much states shown, but there are several threads detected and traced. These threads look too many compared to the ones expected (Figure 2.1). Such apparent inconsistency will be analyzed in section 2.4.

As described in the Introduction, the most common way to instrument an application using Extrae is by using the `LD_PRELOAD` environment variable. This mechanism can be used for any program running "directly" on Linux. For this reason, even if it does not directly affect the Java program, it can be used to instrument the Java Virtual Machine (JVM).

Having a look at the `extraej` script, focusing on the part responsible to launch the program with instrumentation (Code 2.3), it can be seen how it actually uses the `LD_PRELOAD` method. An explanation of `extraej` code can be found in section 2.7.

Code 2.3: Extract of extraej showing the launching command

```
191    LD_PRELOAD=${preload} \
192    CLASSPATH=${cp} \
193      ${JAVA} ${@}
```

---

[2]The class path is the path where the applications, including the JDK tools, look for user classes. The default value of the class path is " . " (dot), meaning that only the current directory is searched. Specifying either the `CLASSPATH` variable or the `-cp` command line switch overrides this value [21]. By default, `extraej` does not override it, and so the compiled `.class` file must be in the current directory, or the `CLASSPATH` variable should be set accordingly.
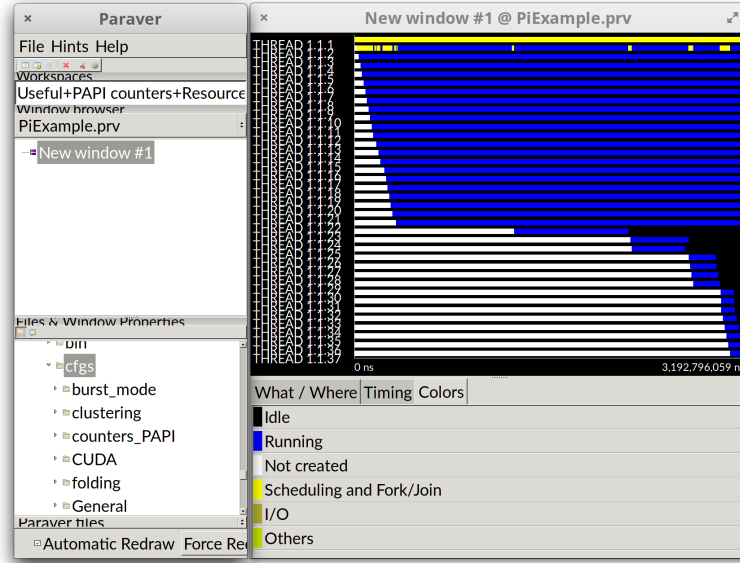
Figure 2.2: PiExample resulting traces. At the bottom a legend for the colors is reported

However, Extrae does not provide any direct instrumentation of the JVM. So how can it extract such data, without any ad-hoc instrumentation probes? The answer can be found in a mechanism that is not strictly related to Java, but to `C` and Linux: pthreads.

2.3 Pthread instrumentation

Pthread is one of the libraries instrumented by Extrae. The probes injection to trace the states of the Linux threads is done by implementing the wrappers of the valuable pthread functions like `pthread_create` or `pthread_join`.

The Java Virtual Machine (JVM) is mostly implemented in C, and for its Linux implementation each Java Thread is mapped on a POSIX thread (pthread) [22]. It is for this reason that Extrae's pthread instrumentation is effective with Java programs too.

However, this instrumentation is not enough to show all the details of a Java execution. Based on this result, it looks like that out of the pthread creation and termination no other pthread calls are employed in the JVM. As an example, it can be seen how in Figure 2.2 the synchronization operations present in the Java

implementation (Code 2.2, the calls to `.join()`) are not traced[3].

To let Extrae use pthread instrumentation, it must be enabled in the `extrae.xml` file as in the following piece of code.

Code 2.4: Extract of the extrae.xml config file

```
13  <pthread enabled="yes">
14    <locks enabled="no" />
15    <counters enabled="yes" />
16  </pthread>
```

2.4   Traces analysis

By looking at the traces, several threads can be seen running throughout the process. The reported events include just "running", "join" and "I/O" events. Without knowing anything about the code and with such poor data gathered by the performance analysis, it would have been almost impossible to understand what each thread is doing. Recalling what the program does, it seems that the number of threads should be lower than the ones appearing on the traces. Indeed, the total should be $1 + 1 + 2 + 4 + 8 = 16$ threads, but on the traces the number of threads is 37.

To understand what is going on, one could try to execute the program with a different number of threads, to see how this additional number of threads behaves. By trying to instrument the sequential single-threaded program, the resulting traces are the one in Figure 2.3.

The first thread looks exactly the same, while in the second one there are some differences related to the absence of the other threads (the yellow chunks are missing). The threads numbered from 3 to 22, instead, look the same in both of the tracefiles. A guess[4] that can be made is that such threads are inherently launched by the JVM for each execution (Figure 2.4).

As we will see in the following chapters, this guess will appear to be mostly correct.

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[3]On top of that, I tried debugging by inserting breakpoints to other pthread calls which were never called. However, this is information is not important. As it will be discussed in later chapters, the tracing activity does not need pthread instrumentation in any case.

[4]The methodology behind performance analysis expects some level of "guessing" when looking at the traces.
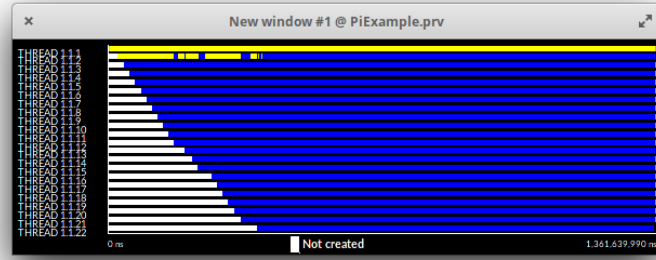
Figure 2.3: Trace of serial PiExample execution

Figure 2.4: PiExample trace guessed explanation

The states shown in the traces (as it is shown in Figure 2.4) are reported in Table 2.1.

These states are valuable, but they're not enough to understand the behaviour of an application. For example, if we didn't know that, we could not say that the main thread was waiting for all the other threads before going forward. It can be deduced of course, but the state of "waiting" is not traced, so that is one event missing. All the valuable events that can be traced will be discussed in chapter 4.

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State	Color	State description
Idle	black	The thread stop existing
Running	blue	The thread is running, that is: it was created and it has not been destroyed yet
Not created	white	The time before the thread was created
Scheduling and Fork/Join	yellow	The thread is launching new threads
Input/Output	dark yellow	The traces are being flushed on disk
Others	light green	Other traced events, not covered by the above states

Table 2.1: Currently traced states for Java threads instrumentation

2.5 Extrae Java API through JNI implementations

When installing Extrae with Java enabled, this will install a basic instrumentation library based on JNI bindings[5]. The purpose of this library is to inject probes manually, by putting events in certain positions of the code during the development phase. This kind of events, however, do not provide any way to signal new threads, but rather they are used as "markers" for specific portions of code, relying on other mechanisms to discover on which thread they're being called—like the pthreads identifiers, in relation to the pthread instrumentation seen earlier.

The JNI implemented library is like a normal class, but with native methods instead of the standard ones. The implementation of these method is made in C language, which has to use specific functions signatures in order to be recognized by Java. In Code 2.5 and Code 2.6 can be seen an extract of the JNI bindings implemented in Extrae.

In brief, thanks to JNI, this implementation allows to call the Extrae API for custom events instrumentation—which is written in C—directly from Java code.

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[5]JNI stands for *Java Native Interface*. The JNI is a native programming interface. It allows Java code that runs inside a JVM to interoperate with applications and libraries written in other programming languages, such as C, C++, and assembly. [23].

Code 2.5: Native methods inside the Java class. The `System.loadlLibrary` call dynamically loads the JNI bindings from a shared library

```java
package es.bsc.cepbatools.extrae;

public final class Wrapper
{
  static { System.loadLibrary("javatrace"); }
  ...
  public static native void Event (int type, long value);
  public static native void Eventandcounters (int type, long value);
  ...
}
```

Code 2.6: C implementation of the "javatrace" library, that will be associated to the Java native methods. Notice the name of the function, that must report the package, class and method name separated by a _.

```c
...
JNIEXPORT void JNICALL
Java_es_bsc_cepbatools_extrae_Wrapper_Event (JNIEnv *env,
  jclass jc, jint id, jlong val)
{
    Extrae_event ((extrae_type_t)id, (extrae_value_t)val);
}

JNIEXPORT void JNICALL
Java_es_bsc_cepbatools_extrae_Wrapper_Eventandcounters (
  JNIEnv *env, jclass jc, jint id, jlong val)
{
    Extrae_eventandcounters ((extrae_type_t)id, (extrae_value_t)val);
}
...
```
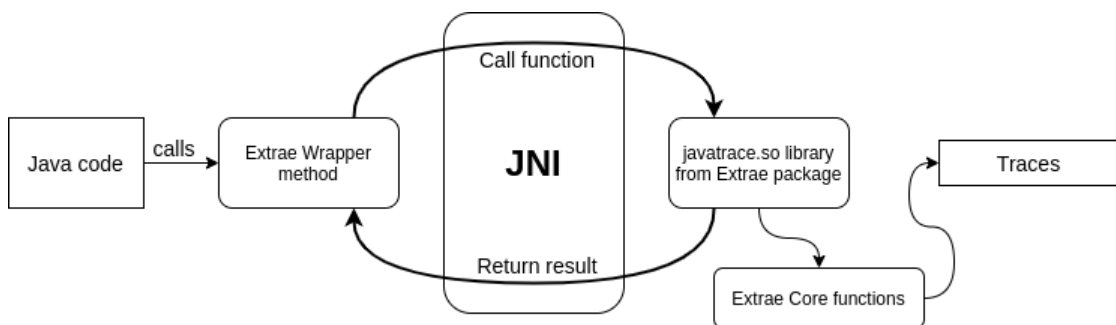

Figure 2.5: Explanation of JNI implemented Extrae wrappers

2.6 Experimental features

Besides the features presented in this chapter, Extrae's reference presented a couple described as "experimental". Such features were implemented by BSC performance tools collaborators, who don't work at the BSC anymore. For this reason, some of them were never fully implemented, and some others were not working due to some bugs accumulated in years of lack of maintenance.

All of them are explained here in this section.

2.6.1 Java Virtual Machine Tool Interface

The first one is a tracing platform based on the the JVM Tool Interface (JVM TI), a native programming interface thought for tools development. It provides both a way to inspect the state and to control the execution of applications running in the JVM. JVM TI supports the full breadth of tools that need access to JVM state, including but not limited to: profiling, debugging, monitoring, thread analysis and coverage analysis tools. It is available as an API for C/C++, and once the library is implemented, it can be used as an agent for the JVM [24].

Comes naturally to think that it would be a useful tool to be used to gather data for the traces, and it actually is. The idea was to implement it in Extrae, and inject it as an agent when executing the program with `extraej`.

However, despite being present among the features, it was never fully implemented. It was thought to be used as a threads-tracing mechanism instead of pthread, but its only use ended to be tracing the garbage collection events. The problem in using for threads too was about identification, because the JVM does not provide the JVM TI with a unique ID for the threads, which is instead required by Extrae's architecture. Indeed, this one was one of the issues addressed (and solved) in this thesis.

2.6.2 AspectJ for User Functions

The second experimental feature sees AspectJ, an Aspect Oriented Programming[6] extension for Java, as the tool to generate the events for the user functions. In this context, the "user functions" are those functions that the user would like to see on the traces. It should basically do what the JNI bindings were designed for, but in an automatic way by wrapping the target functions with some events, traced by Extrae—and so, placing custom events without modifying the code.

---

[6]An introduction to AOP can be found in the next chapter.

Indeed, wrapping the methods with some code is basically the main purpose of AspectJ—and more in general of the Aspect Oriented Programming paradigm. The wrapper code calls the JNI implemented Extrae API library introduced in the previous section to trace the user functions events. The target user functions are listed in a file, whose path is passed to Extrae through the XML configuration file (i.e. `extrae.xml`).

This feature was also not working, but this time due to some bugs in the installation process. Once fixed, it was possible to use the "User functions" configuration of Paraver to look at them (Figure 2.6).
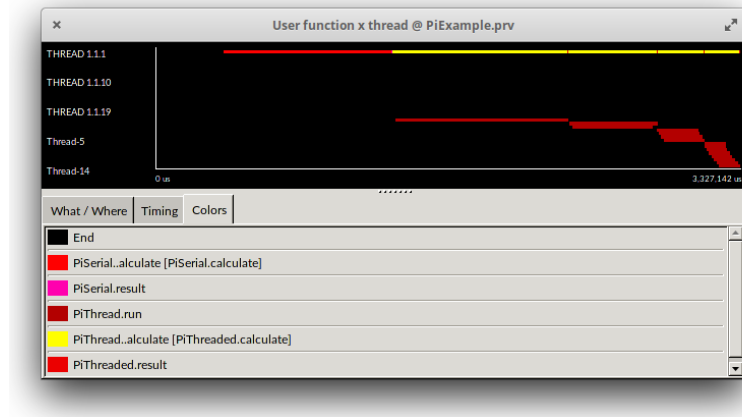
Figure 2.6: Trace showing the user functions for the PiExample program

2.7 Meet extraej

Finally, since it will be modified throughout the thesis, the state of the art version of `extraej` is worth a mention.

As said previously, `extraej` is a bash script made to launch Java applications with instrumentation. It gets some simple optional parameters:

- `-v` makes execution verbose;
- `-keep` saves the temporary files for a future use;
- `-reuse <dir>` to reuse previously instrumentation files (kept using `-keep`).

The structure of the script is quite simple. It works with some environment variables, that point to the different Extrae libraries. The main part makes all the checks for a safe execution, parses parameters and XML config file, generates the aspects for the user functions (if specified in the config file) and finally executes the Java

application. The main part of `extraej` (lightened of the trivial checks) is reported in Code 2.7.

Code 2.7: Main part of `extraej`

```bash
#!/bin/bash
...
# Parse extraej parameters
parse_parameters "${@}"

# Do we support AspectJ?
if [[ -x "${AJC}" ]]; then
    ...
        # parse config file
    parse_xml ${EXTRAE_CONFIG_FILE}

        # do we have user functions to instrument?
    if [[ ${#MemberArray[@]} -gt 0 ]]; then
        tmpdir=`mktemp -d extraej.XXXXXX`

        generate_aspects

        # compile the generated aspects
        CLASSPATH=${ASPECTWEAVER_JAR}:${EXTRAEJ_JAVATRACE_PATH}:${
    CLASSPATH} \
        ${AJC} \
         -inpath . \
         -sourceroots ${tmpdir}/aspects \
         -d ${tmpdir}/instrumented
        if [[ "${?}" -ne 0 ]]; then
          die "Error! ${AJC} failed"
        fi

        execute_java ${tmpdir}/instrumented:${ASPECTWEAVER_JAR}:${
    CLASSPATH} \
            ${EXTRAEJ_LIBPTTRACE_PATH} \
            "$@"
    ...
else
  # We don't support AJC. Let's execute the code with Extrae support
  execute_java "${CLASSPATH}" \
    ${EXTRAEJ_LIBPTTRACE_PATH} \
    "$@"
fi
...
```

And `execute_java` is implemented as follows (Code 2.8). It receives the class path and the preload as arguments, it checks for the JVM TI library availability and in case sets it as the agent.

21

Code 2.8: Implementation of `execute_java` procedure

```
execute_java () {
  local cp=${EXTRAEJ_JAVATRACE_PATH}:$1 # Class path
  shift
  local preload=$1      # Preload library (LIBPTTRACE)
  shift

  # Check whether Extrae supported JVMTI
  if [[ ! -r ${EXTRAEJ_LIBEXTRAEJVMTIAGENT_PATH} ]]; then
    LD_LIBRARY_PATH=`dirname ${EXTRAEJ_LIBEXTRAEJVMTIAGENT_PATH}`:${
    LD_LIBRARY_PATH} \
    LD_PRELOAD=${preload} \
    CLASSPATH=${cp} \
        ${JAVA} ${@}
  else
    LD_LIBRARY_PATH=`dirname ${EXTRAEJ_LIBEXTRAEJVMTIAGENT_PATH}`:${
    LD_LIBRARY_PATH} \
    LD_PRELOAD=${preload} \
    CLASSPATH=${cp} \
        ${JAVA} -agentpath:${EXTRAEJ_LIBEXTRAEJVMTIAGENT_PATH} ${@}
  fi
}
```

2.8 Where to go from here

In this overview there are some specific issues that emerged.

The first issue to be addressed is the lack of specific events related to Java. The only ones traced by Extrae totally rely on the pthreads instrumentation. Moreover, as pointed out in section 2.4, the traced events and states are not detailed enough to give a proper idea of the behaviour of an application.

The second one is the presence of some bugs on the already present Java instrumentation, that make Extrae not working properly with Java programs. Mainly, these bugs are related to installation issues, which used to make unavailable some features when trying to use them. Although this process has been carried out in parallel to the rest of the work, the bug-fixing operations will be omitted in the thesis discussion—unless they are particularly related to the objective, or some interesting cause and solution were found.

The final one is the absence of a mechanism to trace distributed applications. Since it is probably the most common way of executing Java on HPC, it would be interesting to inspect this field and try to find a solution for this problem.

These issues will be the basis of the work developed next. Although not all of them

have been studied throughout the thesis, they have been all kept in mind when discussing the different approaches and developing the solutions to the various problems.

Chapter 3

Java Tracing Methodologies

The main focus of this thesis is on Extrae, because the main issue is on extracting the application performance details from Java program, and not on how to visualize them. Indeed, as it has been said in the Introduction, Paraver is quite flexible and does not need any change in the code to effectively depict the events for a new instrumented framework.

Since Extrae is implemented in `C`, generating probes and wrappers would not be an issue for other C-implemented programs. Unfortunately, generating traces for a Java program cannot be so straight forward, but there are some approaches that could be tried out to extract the data needed to generate an effective trace. In this chapter there is an overview of the approaches studied in this thesis.

NB: all the discussed approaches, in order to trace the events, need to interface with Extrae's functions at some point. Such events must be coded and globally identified through the use of some constants. However, besides this small clarification, all the implementation details of such approaches are left for the next chapters.

3.1   Linker Preload approach

Once got used to Extrae, the first approach that comes to mind is the one of instrumenting the JVM using the linker preload. This kind of instrumentation expects to find the valuable functions inside the JVM, in order to define some wrappers for them, with the purpose of injecting the probes responsible for the tracing activity.

Although valuable for many frameworks, in this case this approach has not been analyzed at all. JVM internals are not standardized, and so they are not defined and immune to changes. There is no way to know that some function used in one version will be maintained in successive releases. For this reason, despite being worth a mention because of its relatedness with Extrae's standard approach, it will not be discussed further—except for possible comparison purposes.

3.2   Event-driven instrumentation

A more convenient way to trace the JVM states would be by catching the JVM events. This kind of work can be done thanks to the interface provided by the Java language: the JVM Tool Interface (JVM TI).

This approach expects to use an event-driven platform, in which the events launched by the JVM are catched by some functions containing the tracing instructions. The JVM TI allows to do that by setting user-defined callbacks, able to catch several JVM events—like thread start and end, method entry and exit, garbage collection, object allocation, etc. [25]
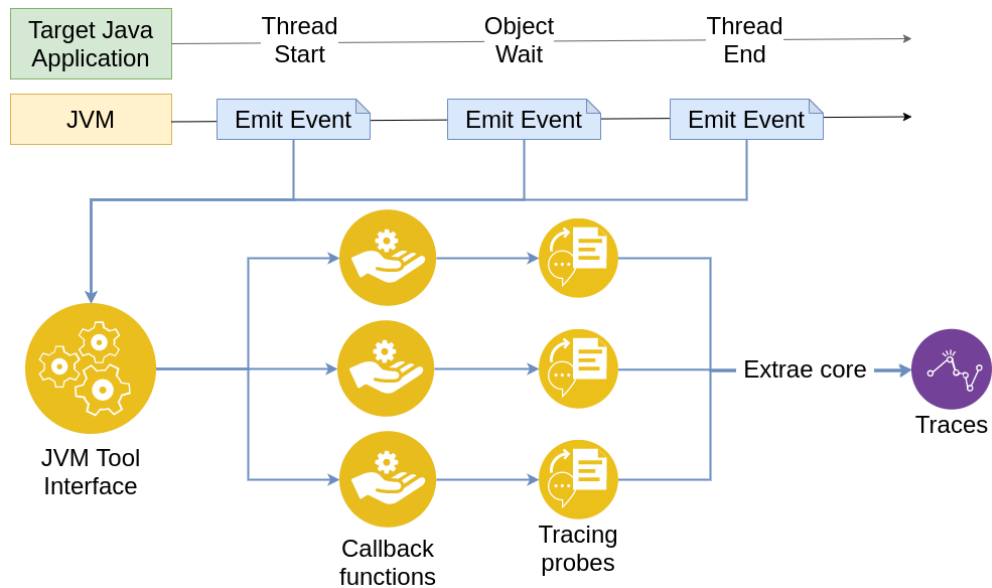
Figure 3.1: Visual explanation of event-driven approach

JVM events are essential for profiling programs, but basing the whole instrumentation on them would be somehow limiting. There are many different events catchable, but there may be interesting data depending on specific functions that do not raise any event. For example, many frameworks use busy-waiting loops implemented

in custom functions to wait for something, instead of the native `Object.wait()` method—that raises an event.

The JVM TI provides two events that may be useful in this case: method entry and method exit events. Such events are raised for each method executed by the JVM, respectively at entry and exit point. To trace some interesting methods it would be enough to monitor all these JVM events, waiting for the interesting ones to trace them using Extrae. Using these events is highly discouraged by the JVM TI reference guide, because of its large impact on performance. Speaking of traces in general, if the retrieved information is valuable, the great overhead generated by a callback function for each method can be acceptable. However, the problem of instrumenting specific functions can be solved in other ways, as it is going to be explained in the following sections.

3.3   Bytecode and Native Instrumentation

Another approach is by instrumenting the specific Java methods, using a technique called "bytecode instrumentation".

Bytecode instrumentation is a way of injecting custom instructions inside other classes, without directly modifying the code. The JVM provides some events and control functions to transform the bytecode of classes and methods and, if enabled to do it, it fires an event when a class or a method are loaded. In both cases, it provides the possibility to catch the event and to read the loaded bytecode, in order to modify it[1] and re-load it again. This possibility is given through the Instrumentation API, available for both the Java language, in the package `java.lang.instrument`, and for the JVM TI, through a specific set of events and functions.

Since the injected instructions are in form of bytecodes, the instrumentation probes need to be in a form of callable Java methods. In the case of Extrae, since it is written in `C` language, such methods must rely on JNI implementations of the probes, either directly (the injected bytecodes call a JNI implemented method) or indirectly (the injected bytecodes call a Java method, which in the end calls one or more JNI implemented methods). The JNI implementations need to be written in `C` language, and these must rely on the Extrae's functions to trace the events.

---

[1]According to JVM TI reference guide [25], the modifications inserted through bytecode instrumentation can only be purely additive. Moreover, it is not possible to add new methods inside a class o to modify the signature of the other methods.
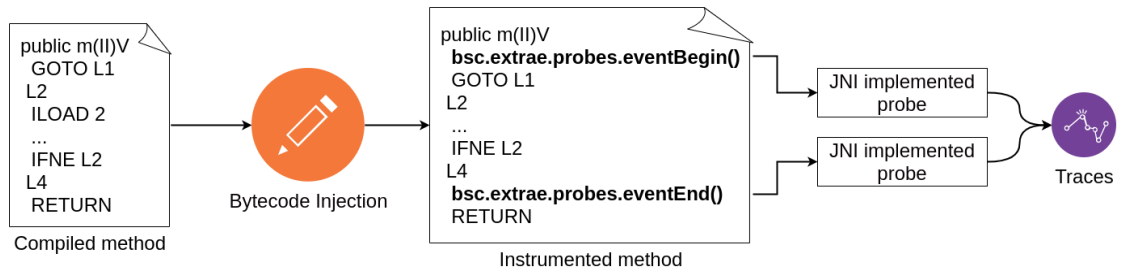
Figure 3.2: Visual explanation of the bytecode instrumentation approach

3.3.1 Bytecode manipulation in C and Java

Injecting bytecode is conceptually easy to understand, but the implementation can be tricky. The JVM provides all the tools to catch when the compiled binary is loaded and to retrieve the related bytecodes. However, these bytecodes are returned in a form of nothing more than long arrays of bytes. Injecting the bytecodes in this binary, requires essentially an intelligent array manipulation work. There are several frameworks implemented in Java for bytecode manipulation[2], but none is available for `C` language[3].

A nontrivial problem is represented by exceptions handling. For its nature, bytecode instrumentation is simply an addition in given program places. For this reason, if the program raises an exception before reaching the end of the method, it would never execute the bytecodes responsible to trace the end of the event. A possible solution would be to catch the event of the Exception raise—available for the JVMTI—and to develop a mechanism to trace the end of the currently traced method.

3.3.2 Native methods instrumentation

Native methods are those methods available to be called in Java, but implemented natively in `C` language. As for the probes discussed in the previous section, this can be done thanks to the JNI. Having a C-implementation, these methods are not compiled in bytecodes, and so are not suitable to be instrumented by injecting bytecodes. This problem is solved by the Instrumentation API, both for Java and the JVM TI, which provides a way to change the name of natively implemented

---

[2]Among the most popular, there are ASM [26] and Javassist [27]

[3]To be fair, I could find one for `C++` [28], but since Extrae is written in C it resulted to be quite complex to cross compile it effectively (I tried, but I had many problems at running time with the linked functions).

methods, by adding a prefix, in order to define a wrapper method (in Java).

In addition, native methods instrumentation, together with other problems, can be solved thanks to the approach explained in the next section: AspectJ.

3.4 Aspect Oriented Programming approach

Aspect Oriented programming (AOP) is a programming paradigm first introduced by G. Kiczales *et al* [29], that aims to add additional behavior to existing code without modifying the code itself. AspectJ, as one of the most popular aspect-oriented frameworks, has been chosen for this thesis.

The way of using it for tracing purposes is similar to the bytecode instrumentation approach, with the only difference in the practical implementation. Instead of using JVM events on loaded classes and inject custom bytecodes, with AspectJ it is possible to define a "pointcut" for each interesting method, and then defining the behaviour of the application before and/or after the execution [30]. This behaviour is implemented as simple Java code and, as it was for the bytecode instrumentation, it would call the JNI methods to trace the specific events.

For tracing purposes AspectJ looks very powerful, because it combines an easy Java implementation of the probes (without bytecode manipulation) and the solution to many problems given by the previous approach, like native methods instrumentation or exception handling.

3.5 Discussion on the methodology to adopt

Before trying there are no definitive conclusions to make. However, there are some approaches more promising than others. The solution proposed in this thesis will not rely on one single approach, but rather a combination of them.

Considering the needs of tracing threads behaviour and specific methods (either native or standard Java methods), the following configurations are viable solutions.

JVM TI based tracing The JVM TI is responsible to trace the events fired by the JVM, but also for the bytecode and native methods instrumentation at each class load time. Exception handling must be managed to keep coherence among the states, and bytecode needs to be manipulated in native language.

AspectJ based tracing The tracing software would rely totally on AspectJ and JNI implemented probes. Being based on methods and not JVM events, it needs

some care when defining when a new thread is created, since it could happen in different ways.

JVM TI with the aid of Java instrumentation API   The JVM TI is responsible to catch and trace the JVM events, while the Java instrumentation API is responsible to trace the specific methods. Exception handling must be managed to keep coherence among the states, and the native methods should be instrumented using the Java instrumentation API. In the end, JNI methods are needed for the natively implemented probes.

JVM TI with the aid of AspectJ   As the previous case, but employing AspectJ to trace the Java and native methods. Moreover, exception handling can be omitted, since adding behaviour at the end of a method can be done even when an exception is raised, without extra development effort. The drawback, with respect to the previous method, would be the required dependency of AspectJ, that needs to be installed and supported by the OS on which Extrae is going to install.

All of the above solutions require the tracing platform to be compiled as a shared library, in the case of `C/C++`, or a Java archive (JAR), in case of Java and AspectJ. In any case, they need to run as a Java agent during the target application execution.

This thesis considers the JVM TI events as tools of undoubted value. For this reason, the solution studied in the following chapters is based on the last configuration. The JVM TI will be employed for basic events tracing. For methods tracing (native methods included) AspectJ was preferred to bytecode instrumentation because of its flexibility and ease of use (and maintainability)[4].

---

[4]As a side note, it would be fair to say that the first solution based totally on JVM TI would be much appreciated, if Extrae was implemented in `C++`. Being implemented in `C`, it makes bytecode manipulation hard to manage. In `C++`, instead, there are some frameworks available that would have made it much simpler. I made an attempt to implement it and try to compile Extrae by mixing `C` and `C++`, but I couldn't make the linking at run-time to work properly. It would have been nice to create it externally to Extrae and compare it to the AspectJ solution, in terms of usability and generated overhead.

Chapter 4

Basic threads instrumentation with the JVM TI

4.1 JVM Tool Interface preliminaries

4.1.1 JVM TI Events

As said in the previous chapter, one of the features offered by JVM TI is the possibility of setting some callbacks for certain events. There are several available (a complete list of such events can be found on the Reference guide [25]), but the events interesting to be used for tracing purposes are the following:

- Java Thread start: generated by a new thread before its initial method executes;

- Java Thread end: generated by a terminating thread after its initial method has finished execution;

- Monitor Wait: sent when a thread is about to wait on an object;

- Monitor Waited: sent when a thread finishes waiting on an object;

- Contended Monitor Wait: sent when a thread is attempting to enter a Java programming language monitor already acquired by another thread;

- Contended Monitor Waited: sent when a thread enters a Java programming language monitor after waiting for it to be released by another thread;

- Exception: sent when an exception is raised;

- Exception catch: sent when an exception is catched;

- Garbage Collection start: sent when a garbage collection pause begins;[1]

- Garbage Collection end: sent when a garbage collection pause ends;

For each one of these events, a callback can be set.

4.1.2 JVM TI Initialization and Callbacks

Agent On Load

Implementing an agent with JVM TI requires some simple steps. First of all, `jvmti.h` needs to be included. Then, the agent must contain a function called `Agent_OnLoad`, whose structure looks as follows:

Code 4.1: JVM TI Agent On Load structure

```
JNIEXPORT jint JNICALL
Agent_OnLoad(JavaVM *vm, char *options, void *reserved)
{
    ...
    return JNI_OK; // JNI_OK means success
 }
```

This function is invoked when the agent library is loaded. It is used to set up all the functionalities that need to be initialized prior to the JVM.

Enabling capabilities and setting the callbacks

Any operation provided by the JVM TI can be done through an environment object, represented by a structure of type `jvmtiEnv`. To get this environment, it is necessary to call a specific function from the JVM reference, passed by the `Agent_OnLoad` function.

Code 4.2: JVM TI Environment retrieval

```
static jvmtiEnv *jvmti;

JNIEXPORT jint JNICALL
Agent_OnLoad(JavaVM *vm, char *options, void *reserved)
{
```

---

[1]Only stop-the-world collections are reported, that are fired by the collections during which all threads cease to modify the state of the JVM.

```
6        /* Get JVMTI environment */
7        (*vm)->GetEnv(vm, (void **)&jvmti, JVMTI_VERSION);
8
9        ...
10  }
```

Before setting the callbacks for the events, it is necessary to enable the related capabilities.[2]

Code 4.3: JVM TI capabilities example

```
1  jvmtiCapabilities    capabilities;
2
3  /* Enable capability for Garbage Collection events */
4  capabilities.can_generate_garbage_collection_events = 1;
5  //set in the environment
6  (*jvmti)->AddCapabilities(jvmti, &capabilities);
```

After that, the pointer to the function can be stored into a specific data structure, which needs to be set in the JVM environment (represented by a `jvmtiEnv` structure). The signature of the callback function depends on the event and is reported in the reference guide [25].

Code 4.4: JVM TI event callback example

```
1  /* Setting the pointer to our callback function */
2  callbacks.GarbageCollectionStart   = &GarbageCollector_begin_callback;
3  //set in the environment
4  (*jvmti)->SetEventCallbacks(jvmti, &callbacks, sizeof(callbacks));
```

Finally, it is necessary to enable the events notifications.

Code 4.5: JVM TI notification enabling example

```
1  (*jvmti)->SetEventNotificationMode(jvmti, JVMTI_ENABLE,
2      JVMTI_EVENT_GARBAGE_COLLECTION_START, NULL);
```

Although the JVM TI environment can be stored in a global variable and used everywhere at any time, all these operations should be preferably executed inside the `Agent_OnLoad` function, because enabling events and callbacks are part of those operations that should be set before the JVM initialization [25].

---

[2]A capability is simply the ability of the JVM TI to do some operation.

Probes injection

As it can be imagined, the instructions to trace these events (i.e. the probes) will be contained in the callback functions. One event should be related to one callback, with its specific constant ID. The implementation details of such probes will be addressed in the next section.

Compiling the library and setting the agent

The JVM TI needs to be implemented and compiled as a shared library. After that, it is necessary to tell the JVM to use it as an "agent", by launching the Java program with the `-agentpath` option set to the path of the agent library.

```
java -agentpath:<path_to_jvmti_agent_library> <target>
```

The compilation will be managed by the `Makefile`[3], which builds and installs a shared library named `libextrae-jvmti-agent.so`. Passing the agent path as the argument will be managed by `extraej` (Code 2.3).

4.2   Tracing platform implementation

To start generating effective traces, it is necessary to define how to identify one thread, how to gather the right events and how to associate the right events to the right threads. For the Extrae core, two distinct classes of functions are going to be implemented:

- **Probe functions**, responsible to trace the specific event;

- **Backend functions**, responsible to manage the under the cover work, like notifying a new thread, giving an ID, etc.

More in general, all the Java tracing related code has been organized as follows (respecting the pre-existing Extrae source files organization):

- `tracer/wrappers/JAVA` for the above mentioned *probe* and *backend* functions;

- `java-connector/jni` for the JNI methods implementations (will depend on the previous);

- `java-connector/jvmti-agent` for the JVM TI shared library that is going to be the Java agent;

---

[3]Extrae uses `automake` to manage the entire build. The implementation details of the `Makefile` will not be explicitly reported.

- `java-connector/aspectj` for the Aspects implementation;

- `launcher/java` for the `extraej` launcher script;

- `merger/paraver` for the code responsible to translate the events into proper Paraver tracefiles.

Each of the previous directory will contain a `Makefile` to create the library (be it a Java archive or a shared library).

4.3 Thread identifier and Backend

4.3.1 Defining the identifier

The main problem of using the JVM TI to notify new threads is the identifier, needed by Extrae to associate the events to the right threads. When instrumenting with pthread instrumentation, that value was a pthread key[4] set by Extrae. However, by using the JVM TI to trace the different threads, the pthread instrumentation must be disabled, and with it also its thread identification mechanism. Without a defined identifier for each thread, the result would be something like Figure 4.1, in which the events are inordinately traced all on a unique thread.
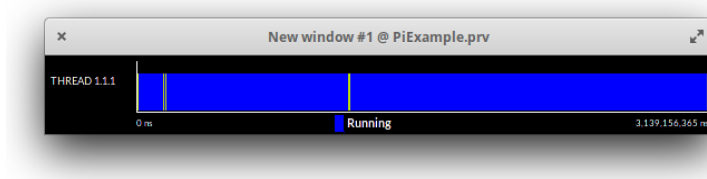
Figure 4.1: Example of traces without a defined thread identifier

Although the Java threads have an identifier, this is not available for the JVM TI[5]. Since all the Java threads are mapped on pthreads [22], even if they can't rely on the same backend functions of pthread instrumentation, they can build the

---

[4]`pthread_key_t` is a type of variable, initialized using the `pthread_key_create()` function and set using `pthread_setspecific()`. The create function shall create a thread-specific data key visible to all threads in the process. Key values are opaque objects used to locate thread-specific data. The same key value may be used by different threads, bu the values bound to the key by `pthread_setspecific()` are maintained on a per-thread basis and persist for the life of the calling thread. That means that it can be used to store a different ID for each a thread, retrieving it when needed using `pthread_getspecific(pthread_key)` [31].

[5]In Java, the method `Thread.getId()` returns a unique ID. However, in the thread data given by the JVM TI environment, no such ID is present. [25]

same mechanism. Following Extrae's naming convention, the Java instrumentation backend will be implemented in a file named `java_wrapper.c`, whose header file will be `java_wrapper.h`. Both the files will be contained in the proper directory, as explained previously.

4.3.2 Backend implementation

Generating the pthread identifier is done using a `pthread_key_t` global variable, that needs to be created once for all and then used by each thread to set its own ID. The creation is contextual to the initialization, so the following solution has been developed (Code 4.6).

Code 4.6: Extrae Java Backend initialization

```c
#include "common.h"
#include "threadid.h"
#include "wrapper.h"
#include <pthread.h>

static pthread_key_t   pThreadIdentifier;

void Extrae_Java_Backend_init(void)
{
    // if Extrae disabled or pthread tracing enabled return
    if (! EXTRAE_ON() || Extrae_get_pthread_tracing()) return;

    // if not initialized, init Extrae
    if (! EXTRAE_INITIALIZED()) Extrae_init();

    // create pthread_key
    pthread_key_create(&pThreadIdentifier, NULL);
}
```

For each thread, the ID needs to be set when starting. Moreover, a unique ID value must be generated. A simple choice for a unique ID, is the current number of threads. This choice is not perfect, it has some pros and cons[6].

Extrae provides some backend functions to interact with the core, including the ones to define the number of threads.

---

[6]The consequences of this approach consist in defining the number of threads as the cumulative number, instead of the number of active threads. Doing otherwise would lead to duplicated Thread IDs (for the active ones), which can't happen for Extrae. The drawback is that defining the IDs in this way means also that the ID of a terminated thread cannot be re-utilized, making Paraver to waste much space to represent them in different lines. This approach, compared to the other solutions, has also some pros. A discussion on this is present in subsection 4.6.2.

Code 4.7: Setting the thread ID and changing the number of threads

```
1  void Extrae_Java_Backend_NotifyNewThread(void)
2  {
3      if (!EXTRAE_ON() || !EXTRAE_INITIALIZED() ||
       Extrae_get_pthread_tracing()) return;
4
5      int numthreads = Backend_getNumberOfThreads();
6      pthread_setspecific (pThreadIdentifier, (void*)((long) numthreads
       ));
7      Backend_ChangeNumberOfThreads (numthreads+1);
8  }
```

Being a multi-thread program by definition, a mutex must be added to keep the operation safe. In addition, Extrae must know the current thread ID to operate with the tracing operations. For this reason, it needs to know how to retrieve both the ID and the number of threads at any time (it lets to do so thanks to `Extrae_set_threadid_function` and `Extrae_set_numthreads_function` functions, whose parameters are pointers to functions—see Code 4.8). After some refactoring, the code looks as in Code 4.8.

Code 4.8: Refactored code to notify a new Java thread in Extrae

```
1  #include "common.h"
2  #include "threadid.h"
3  #include "wrapper.h"
4  #include <pthread.h>
5
6  static pthread_key_t   pThreadIdentifier;
7  static pthread_mutex_t  pThreadIdentifier_mtx;
8
9  void Extrae_Java_Backend_init(void)
10 {
11     if (! EXTRAE_ON() || Extrae_get_pthread_tracing()) return;
12     if (! EXTRAE_INITIALIZED()) Extrae_init();
13
14     // Tell Extrae how to retrieve current thread ID
15     Extrae_set_threadid_function(
       Extrae_Java_Backend_GetThreadIdentifier);
16     // Tell Extrae how to retrieve current number of threads
17     Extrae_set_numthreads_function(
       Extrae_Java_Backend_GetNumberOfThreads);
18     // Init identifier
19     Extrae_Java_Backend_CreateThreadIdentifier();
20 }
21
22 void Extrae_Java_Backend_CreateThreadIdentifier(void)
23 {
24     pthread_key_create (&pThreadIdentifier, NULL);
```

```
25        pthread_mutex_init (&pThreadIdentifier_mtx, NULL);
26 }
27
28 unsigned Extrae_Java_Backend_GetThreadIdentifier(void)
29 {
30        return (unsigned) ((long)pthread_getspecific(pThreadIdentifier));
31 }
32
33 unsigned Extrae_Java_Backend_GetNumberOfThreads() {
34    return (unsigned) Backend_getNumberOfThreads ();
35 }
36
37 void Extrae_Java_Backend_SetThreadIdentifier(int ID)
38 {
39        pthread_setspecific (pThreadIdentifier, (void*)((long) ID));
40 }
41
42 void Extrae_Java_Backend_NotifyNewThread(void)
43 {
44        if (!EXTRAE_ON()  ||  !EXTRAE_INITIALIZED()  ||
45     Extrae_get_pthread_tracing()) return;
46
47        pthread_mutex_lock (&pThreadIdentifier_mtx);
48        int numthreads = Backend_getNumberOfThreads();
49        Extrae_Java_Backend_SetThreadIdentifier (numthreads);
50        Backend_ChangeNumberOfThreads (numthreads+1);
51        pthread_mutex_unlock (&pThreadIdentifier_mtx);
52 }
```

4.4   Notify the new threads

Once the backend is ready, it needs to be called by the JVM TI agent[7]. The
JVM TI's event `JVMTI_EVENT_THREAD_START` is going to be used for this purpose.
First of all a callback that calls the backend functions needs to be implemented
(Code 4.9).

---

[7]Reminder: the file now is different. So the Java backend functions need to be included.
Moreover, the library needs to be linked using automake.

Code 4.9: Thread start event callback

```
#include "java_wrapper.h"

static void JNICALL Extraej_cb_Thread_start (jvmtiEnv *jvmti_env,
    JNIEnv* jni_env, jthread thread)
{
    jvmtiThreadInfo ti;
    jvmtiError r;

    r = (*jvmti_env)->GetThreadInfo(jvmti_env, thread, &ti);
    // check if it is a valid thread
    if (r == JVMTI_ERROR_NONE){
        Extrae_Java_Backend_NotifyNewThread();
    }
}
```

Secondly, by following the same steps explained in section 4.1, the following lines need to be added to the `Agent_OnLoad` function (Code 4.10, lightened of the trivial checks).

Code 4.10: Enabling and setting the callback for the Thread start event

```
JNIEXPORT jint JNICALL
Agent_OnLoad(JavaVM *vm, char *options, void *reserved)
{
    jint                rc;
    jvmtiError          r;
    jvmtiCapabilities   capabilities;
    jvmtiEventCallbacks callbacks;

    /* Init backend */
    Extrae_Java_Backend_init();

    /* Get JVMTI environment */
    rc = (*vm)->GetEnv(vm, (void **)&jvmti, JVMTI_VERSION);

    /* Get/Add JVMTI capabilities */
    memset(&capabilities, 0, sizeof(capabilities));
    // no capabilities required for Thread Start event
    r = (*jvmti)->AddCapabilities(jvmti, &capabilities);

    /* Set callbacks */
    memset(&callbacks, 0, sizeof(callbacks));
    callbacks.ThreadStart    = &Extraej_cb_Thread_start;

    r = (*jvmti)->SetEventCallbacks(jvmti, &callbacks, sizeof(
    callbacks));
```

```
    /* Enable event notification */
    r = (*jvmti)->SetEventNotificationMode(jvmti, JVMTI_ENABLE,
            JVMTI_EVENT_THREAD_START, NULL);


    return JNI_OK;
}
```

After the new threads notification mechanism is ready, by instrumenting the same example of chapter 2, the result is shown in Figure 4.2.
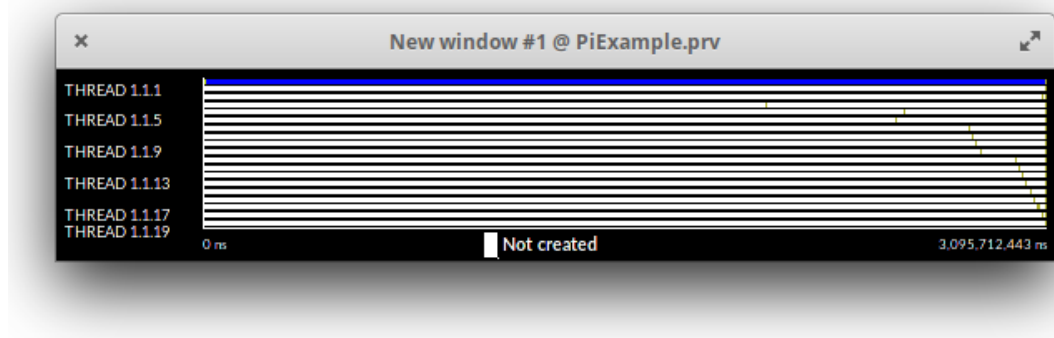
Figure 4.2: Trace with the new thread notification mechanism

As it was explained in section 2.4, the total number of threads should be 16. With pthread instrumentation it was 37, now it lowered to 19. Since no states are shown, to understand what is going on more events are necessary.

4.5 Tracing the events

4.5.1 Events IDs

First of all, an event to notify the running thread is needed. What has been done in the previous section was just a notification to Extrae on the number of threads, but it does not have any clue if the thread is running or not.

Defining and tracing new event requires two simple steps: creating a constant and unique event ID and call the Extrae internal functions to trace such event.

In addition to those, to show the events on Paraver, it is necessary to define the "semantics" of the states generated by those events and some "events description", needed to create some configuration files to show those events on Paraver in a

custom way[8].

The chosen ID must be placed in the `events.h` file (Code 4.11).

Code 4.11: Java events IDs in `events.h` (the other IDs were pre-existent)

```
241  #define JAVA_BASE_EV                   48000000
242
243  #define JAVA_GARBAGECOLLECTOR_EV       48000001
244  #define JAVA_EXCEPTION_EV              48000002
245  #define JAVA_OBJECT_ALLOC_EV           48000003
246  #define JAVA_OBJECT_FREE_EV            48000004
247  #define JAVA_THREAD_RUN_EV             48000005  /* NEW EVENT */
```

4.5.2 Probes implementation

After having defined the ID, it needs to be traced. Such event, has a beginning and an end, so it needs to be traced twice with two different values (0 for the end and 1 for the beginning)[9]. In order to do that it is necessary to do the following:

- Add the JVM TI Thread End event callback;

- Add two new probes to trace begin and end for the event;

- Call these two probes from the Thread Start and Thread End callbacks.

Again, to follow Extrae's naming convention, these probes are implemented in a file called `java_probe.c` (Code 4.12).

Code 4.12: Probes to trace the Running Thread event in `java_probe.c`

```
1  #include "common.h"
2
3  #include "threadid.h"
4  #include "wrapper.h"
5  #include "trace_macros.h"
6
```

---

[8]Until now, the view of Paraver that has been used to show the traces was the "states" view. That means that shows the state records of the application, which represent intervals of actual thread status or resource consumption [19]. In addition, the events must have some differentiating values to let Paraver distinguish them (for example, to give them different colors). These values cannot be the events IDs alone, but they should be normalized for Paraver. This aspect will be explained later.

[9]This choice is also attributable to the Paraver semantics. Once they're traced, Paraver normally manages the traces by looking at the "last value" of the events. So, when the event is traced with value 1 at the beginning, means that the event will remain "Up" until it's going to be set to 0 again (the end).

40

```
7  #include "java_probe.h"
8
9  void Extrae_Java_Probe_Thread_start(void)
10 {
11     if (! EXTRAE_ON()) return;
12
13     if (EXTRAE_INITIALIZED() && !Extrae_get_pthread_tracing())
14     {
15         Backend_Enter_Instrumentation (); // Enter instrumentation
    for this thread
16
17         /* Trace JAVA_THREAD_RUN_EV with EVT_BEGIN value */
18         TRACE_MISCEVENTANDCOUNTERS(TIME, JAVA_THREAD_RUN_EV,
    EVT_BEGIN, EMPTY);
19     }
20 }
21
22 void Extrae_Java_Probe_Thread_end(void)
23 {
24     if (! EXTRAE_ON()) return;
25
26     if (EXTRAE_INITIALIZED() && !Extrae_get_pthread_tracing())
27     {
28         /* Trace JAVA_THREAD_RUN_EV with EVT_END value */
29         TRACE_MISCEVENTANDCOUNTERS(TIME, JAVA_THREAD_RUN_EV, EVT_END,
    EMPTY);
30
31         Backend_Leave_Instrumentation (); // Leave instrumentation
    for this thread
32     }
33 }
```

Notice how it checks for the pthread tracing activity, in order to avoid conflicts between the different events.

4.5.3   JVM TI Callbacks

Once implemented, these probes can be called by the JVM TI callbacks (Code 4.13). In addition to just tracing the event, Extrae gives the chance of setting the name of the thread, by calling the `Extrae_set_thread_name` function. Since the JVM TI gives the name of the thread among the info, it can be useful to retrieve this information (Code 4.13, line 16).

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Code 4.13: Probes called by the JVM TI agent

```c
#include "java_wrapper.h"
#include "java_probe.h"

static void JNICALL
Extraej_cb_Thread_start(jvmtiEnv *jvmti_env, JNIEnv* jni_env, jthread
    thread)
{
  jvmtiThreadInfo ti;
  jvmtiError r;

    if (thread != NULL)
    {
        r = (*jvmti_env)->GetThreadInfo(jvmti_env, thread, &ti);

        if (r == JVMTI_ERROR_NONE && ti.thread_group){
            // Notify new thread
            Extrae_Java_Backend_NotifyNewThread();

            // Set the name given by Java to the thread
            unsigned threadid = THREADID;
            Extrae_set_thread_name(threadid, ti.name);

            // Trace the start event
            Extrae_Java_Probe_Thread_start();
        }
    }
}

static void JNICALL
Extraej_cb_Thread_end (jvmtiEnv *jvmti_env, JNIEnv* jni_env, jthread
    thread)
{
    // Trace the end event
    Extrae_Java_Probe_Thread_end();
}
```

Code 4.14: Setting the callback to the JVM TI environment

```c
JNIEXPORT jint JNICALL
Agent_OnLoad(JavaVM *vm, char *options, void *reserved)
{
    ...
    callbacks.ThreadEnd = &Extraej_cb_Thread_end;
    ...
    r = (*jvmti)->SetEventNotificationMode(jvmti, JVMTI_ENABLE,
                    JVMTI_EVENT_THREAD_END, NULL);
    ...
    return JNI_OK;
```

```
}
```

4.5.4 Paraver states semantics

Finally, to show the results of these events on the trace, the semantics must be defined. Doing so is necessary to let Paraver know which state correspond to which event. There are several states in Paraver [19, p. 20], but for now the interesting ones for the thread execution are: "Idle" and "Running".

In complex cases, the correlation between states and events may be dependent on several factors (i.e. an event can generate different states based on the current one), but for now this definition will be straight forward: when the Thread Running event begins, the state must be "Running", when it ends it becomes "Idle".

To do so, it is enough to tell the merger[10] how to interpret the events. The java functions for the merger are contained in the file `merger/paraver/java_prv_semantics.c`, which contains a list of key-value pairs, where the key is the event ID and the value an handler function for each Java event[11]. To trace the state, it was enough to add the handler in the list and a call to the `SwitchState` function (Code 4.15). When the value of the event (`EvValue`) is different from the end, the state is Up. Otherwise, it would be set down (and other overlapping states are shown, if any).

Code 4.15: Semantics for the thread running event (`java_prv_semantics.c`)

```
SingleEv_Handler_t PRV_Java_Event_Handlers[] = {
  { JAVA_GARBAGECOLLECTOR_EV, JAVA_call },
  { JAVA_EXCEPTION_EV, JAVA_call },
  { JAVA_THREAD_RUN_EV, JAVA_call }, /* NEW HANDLER RECORD */
  { NULL_EV, NULL }
};

static int
JAVA_call (event_t* event, unsigned long long current_time,
  unsigned int cpu, unsigned int ptask, unsigned int task,
  unsigned int thread, FileSet_t *fset )
{
  unsigned EvType;
  unsigned long long EvValue;
```

---

[10]By "merger" is simply meant the part of the application responsible to translate all the events in another format. In the specific case, it is referring to the "Paraver merger", and so it is the final part of the instrumentation, in which the events are being reported to a Paraver trace file.

[11]This list is parsed by Extrae's merger for Paraver. It simply scans all the lists for all the instrumented frameworks, calling the right handler based on the event found.

```
EvType  = Get_EvEvent (event);
EvValue = Get_EvValue (event);
switch (EvType)
{
  case JAVA_GARBAGECOLLECTOR_EV:
  case JAVA_EXCEPTION_EV:
    Switch_State (STATE_OTHERS, (EvValue != EVT_END), ptask, task,
  thread);
    break;
  case JAVA_THREAD_RUN_EV: /* NEW CASE */
    Switch_State (STATE_RUNNING, (EvValue != EVT_END), ptask, task,
  thread);
    break;
}

trace_paraver_state (cpu, ptask, task, thread, current_time);
trace_paraver_event (cpu, ptask, task, thread, current_time,
              EvType, EvValue);

return 0;
}
```

The result of all these operations can be found in Figure 4.3. As it can be seen, now the traces are showing the running state.
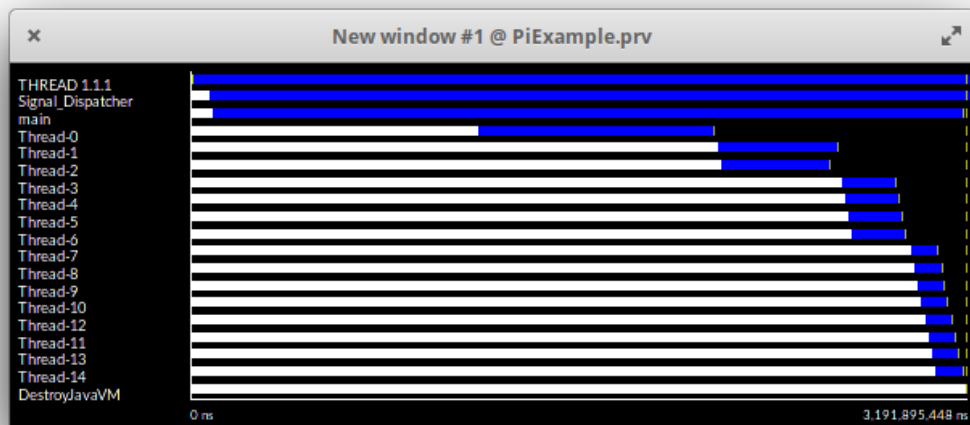
Figure 4.3: Traces with Thread Running state and thread names given by the JVM TI

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4.5.5 Tracing the remaining events

The other JVM TI events need to be traced. As it has been done for the running event, all of them will be associated to a unique ID and to some state in the Paraver tracefile. Having a look to the list of the interesting JVM TI events (subsection 4.1.1), there are some missing to trace. In Table 4.1 there are all the events summarized with the related Extrae event and Paraver state.

Each of them can be traced by using a callback that calls a specific probe. The resulting traces are shown in Figure 4.4.
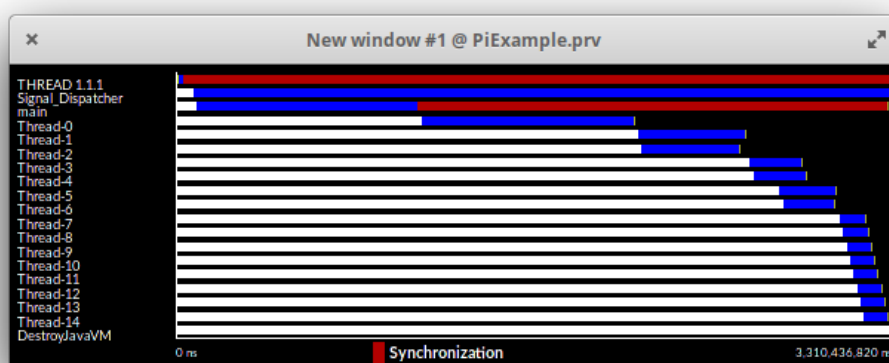
Figure 4.4: Traces with all the JVM TI events traced

JVM TI Event	Extrae Event Type	Event Value	Next State
Thread Start*	JAVA_THREAD_RUN_EV	Begin (1)	Running
Thread End*	JAVA_THREAD_RUN_EV	End (0)	Idle
Monitor Wait	JAVA_WAIT_EV	Begin (1)	Synchronization
Monitor Waited	JAVA_WAIT_EV	End (0)	*back to previous*
Contended Monitor Wait	JAVA_WAIT_EV	Begin (1)	Synchronization
Contended Monitor Waited	JAVA_WAIT_EV	End (0)	*back to previous*
Exception	JAVA_EXCEPTION_EV	Begin (1)	Others
Exception Catch	JAVA_EXCEPTION_EV	End (0)	*back to previous*
Garbage Collector start	JAVA_GARBAGECOLLECTOR_EV	Begin (1)	Others
Garbage Collector end	JAVA_GARBAGECOLLECTOR_EV	End (0)	*back to previous*

Table 4.1: Summary table for the traced Thread events and related states. The events marked with an asterisk * are disabled when pthread tracing is enabled.

4.6 Discussion of the partial results

4.6.1 Traces analysis

In this chapter the platform on which all the tracing activity will rely on has been implemented. A thread notification system has been designed and the events are starting being traced.

Moreover, in subsection 4.5.3, a name was set to the thread. Indeed, this name can be found on the left side of both Figure 4.3 and Figure 4.4. Thanks to that, it is easy to recognize what these threads are, and for some of them even their purpose is promptly clear. Although not really informative yet, the traces are becoming to shape themselves.

4.6.2 Thread IDs

Defining the thread IDs how it is explained in this chapter leads to some consequences. The identification is done by the cumulative number of threads, which means that the threads take an increasing ID starting from 1, and the terminated threads will not see their ID re-utilized by other threads. This is the same approach applied by the pthread instrumentation.

The alternative to this approach would be a mechanism to assign IDs starting from 1, by keeping trace of the available ones and generating new IDs only if all the previous are still in use. In math symbols, every new notified thread would get as ID the smallest available m, with: $1 \leq m \leq N+1$, $N = max\{current\_thread\_IDs\}$. In other words, if at a given time the highest ID is N and a new thread is being notified, this new thread would get $N+1$ if and only if all the IDs from 1 to N are taken by active threads; otherwise, the new thread ID would be the smallest m available. This approach is the same used by the OpenMP instrumentation.

If for OpenMP this is the only approach that makes sense, for Java threads or pthreads it makes less sense. This assertion is based on the fact that the OpenMP threads are simple workers, while the Java threads can be specialized units with specific names, and making them share the same ID and "line" (on Paraver), would probably lead to confusions. For this reason, this solution has not been implemented in this thesis.

However, there are some frameworks that work in a fashion similar to how OpenMP works for Java[12]. Such special cases can be dealt separately, or this feature can be implemented and activated only if needed.

---

[12]The ForkJoin framework is often compared to OpenMP, for example.

4.6.3 Would JVM internal instrumentation provide any added value?

As said in the previous chapter, instrumenting the JVM internals would lead to inconsistencies, soon or later. However, even ignoring this aspect, one doubt can be: would it be possible to gather more valuable data by instrumenting it anyway?

To discover some relations between the JVM events and its internal functions, I observed the execution of some Java programs using `gdb`[13]. By putting breakpoints in the JVM TI callbacks, inspecting the call stack and spending some time to analyze different programs, I discovered that most of the valuable events and interesting functions correspond to some of the above events. Instrumenting such functions, would not give any additional information respect to the events and data provided by the JVM TI. The only exception is the "Object notify" event: when it happens, always the same internal function is called, but it does not raise any event. However, `Object.notify()` is a native method, and it can be instrumented in other ways.

In conclusion, the JVM TI makes it pointless to even try the manual instrumentation of the JVM internal functions. And this is also true thanks to the next tool that is going to be employed in this study, and that will be explained in the next chapter: AspectJ.

---

[13]GDB is the GNU Project Debugger, a debugger that can be used for many languages (`C` and `C++` included). It allows to set breakpoints, stop the program on certain conditions, inspecting local variables or the call stack and other helpful operations [32].

Chapter 5

AspectJ and other improvements

The JVM TI gives access to a set of very useful events, which can be effectively used to trace the threads states. However, there are still other threads missing to trace, which are not available through the JVM TI. The necessity of a more general approach raises, an approach that is not tied to the JVM events available via the Tool Interface, but one that allows to instrument freely some target methods. Such approach, can be found in the Aspect Oriented Programming, and more specifically in AspectJ.

However, before diving into the implementation of the AspectJ solution, some preliminary work is necessary. Indeed, it would not be possible to instrument complex applications before modifying `extraej`, because it currently does not support custom class paths.

Moreover, recalling the discussion about the events information to depict on Paraver (subsection 4.5.4), the events should be represented in some way other than just the states records.

These improvements will be studied throughout this chapter.

5.1 Setting user class path to `extraej`

The state of the art of `extraej` (section 2.7) needs to be launched in the same directory of the class to instrument, because the standard class path when launching a java application is "." (the current directory). This is limiting for several reasons:

- it lets to instrument only the applications that depend only on the JDK, and not on other frameworks whose classes are placed somewhere else;

- it does not let to instrument most of the applications object of this thesis, since the frameworks are not part of the JDK;

- seen the previous point, and as it will be discussed in section 5.2, the AspectJ's compiler (`ajc`) needs the classes to instrument in the class path to work.

In order to improve this, an option `-cp` was added to `extraej`, and works as follows:

```
extraej -cp <DIRECTORY_OR_FILE> -- <TARGET>
```

That is implemented in order to add to the class path all the containing files if its a directory, or just the file if not[1] (Code 5.1).

Code 5.1: `extraej` new option implementation

```bash
#!/bin/bash
...
parse_parameters () {
    ...
    elif [[ "${1}" = "-cp" ]]; then
      shift
            user_cp=${1}
    ...
}
...
if [[ "${user_cp}" != "" ]]; then
  if [[ -d "${user_cp}" ]]; then
    for cp in $(ls ${user_cp}); do
      CLASSPATH="${user_cp}/${cp}:${CLASSPATH}"
    done
  else
      CLASSPATH=${user_cp}:${CLASSPATH}
  fi
  echo "Updated Classpath: ${CLASSPATH}"
fi
...
```

---

[1]The class path would be enough to point to a directory full of compiled `.class` files. However, this way is more general, because if in the directory are present JAR files (which is quite common when building the dependencies with Maven, for example), they will be added to the class path too.

5.2 AspectJ for Instrumentation

5.2.1 Introduction to AspectJ

AspectJ is a framework to implement aspect-oriented programming Java. In practice, it adds to the Java language just one new concept: a join point. This is implemented and managed through some new constructs: pointcuts, advice, inter-type declarations and aspects.

The official "Getting started with AspectJ" guide [33] defines these new elements as follows:

"A *join point* is a well-defined point in the program flow. A *pointcut* picks out certain join points and values at those points. A piece of *advice* is code that is executed when a join point is reached."

"AspectJ's *aspect*s are the unit of modularity for crosscutting concerns. They behave somewhat like Java classes, but may also include pointcuts, advice and inter-type declarations."

Code 5.2: Example of an *aspect* implementation in AspectJ, with some local attributes and methods, a *pointcut* to define the type of call to catch and an *advice* to add some behaviour one the catched call. The aspects are normally stored in `.aj` files.

```java
import org.aspectj.lang.reflect.*;
import java.lang.*;

aspect PointObserving {
    OutputStream logStream = System.err;
    boolean updatedX = false;

    void logChangeX(int x) {
        logStream.println("about to change X");
    }

    pointcut changeX(): call(void Point.setX(int));
    before(): changeX() {
        updatedX = true;
        logChangeX();
    }
}
```

This instrumentation approach is going to use AspectJ just for calling the probes, which are going to be implemented using JNI[2]. That means, the *pointcut*s will be on the methods to instrument, while the pieces of *advice* will be implemented in order to call the JNI methods[3], as shown in the example Code 5.3.

Code 5.3: Example of instrumented methods using AspectJ

```
import org.aspectj.lang.reflect.*;
import bsc.extrae.JavaProbes;

aspect SomeClassInstrumentation {

    pointcut someOperation(): call(void SomeClass.someMethod(void));

    before(): someOperation() {
        JavaProbes.traceSomeEventBegin();
    }

    after(): someOperation() {
        JavaProbes.traceSomeEventEnd();
    }

}
```

5.2.2 What to trace using AspectJ

Before diving into the development phase, the methods to be instrumented must be decided.

The first event interesting to gather can be found by looking at the traces given by the pthread instrumentation (Figure 2.2) and the ones given by the instrumentation through JVM TI (Figure 4.4). In the second one, even if the synchronization state is present, the "Scheduling and fork/join" state is totally missing. A thread is in this state while it is creating a new thread, and in our example such thread creation is what is done by the `Thread.start()` method[4]. So this is the first method to be

---

[2]The basic concepts of *Pointcut*, *Advice* and *Aspect* are enough to deliver this job. For this reason, this brief overview of AspectJ ends here. AspectJ's power is far beyond solving this simple task, but all the possible features and complex usages won't be explained, because not related to the objective of the thesis. However, any necessary tool will be gradually introduced.

[3]This is almost how it works with the User Functions, explained in section 2.5. The generation was different, but the concept of calling the JNI methods inside the pieces of advice was the same.

[4]Indeed, the Java threads work in this way. In order to run the thread (that means executing what is contained in the Thread Object's `run` method), the `start` method must be called on the Thread object (it can be seen in Code 2.2 too).

traced using AspectJ.

Another event that may be interesting to trace, and of which there are no clue in JVM TI events, is the monitor notification event (`Object.notify()`).

These two (`Thread.start()` and `Object.notifiy()`) will be the first two instrumented methods using AspectJ.

5.2.3 JNI implemented probes

As already stated, the probes must be implemented through JNI bindings, in order to interoperate with Extrae's core in C language. In order to implement the probes using the JNI (recalling section 2.5), it is necessary to define a class with some native methods (Code 5.4).

Code 5.4: Extrae Java instrumentation probes Class

```
package es.bsc.cepbatools.extrae;

public final class JavaProbes
{
    static { System.loadLibrary("javatrace"); }

    public static native void ThreadStartBegin();
    public static native void ThreadStartEnd();

    public static native void ObjectNotifyBegin();
    public static native void ObjectNotifyEnd();
}
```

As it can be seen by Code 5.4, the loaded library is "javatrace", the same of the wrappers in Code 2.5, and also the package is the same. Indeed, the JNI implemented probes are going to end in the same library, in order to keep the same dependencies and `Makefiles`. Indeed, from the implementation point of view, these probes are not different from the functions of the Java Extrae instrumentation API, presented in section 2.5.

The probes are implemented in C language as in Code 5.5, and they will be contained in the same directory of the other JNI bindings (`java-connector/jni`), in a file called `extrae_javaprobes.c`.

Code 5.5: Extrae Java instrumentation probes implementation in C language

```
JNIEXPORT void JNICALL
Java_es_bsc_cepbatools_extrae_JavaProbes_ThreadStartBegin(
  JNIEnv *env, jclass jc)
{
    Extrae_Java_Probe_ThreadStart_begin();
```

```
 6  }
 7
 8  JNIEXPORT void JNICALL
 9  Java_es_bsc_cepbatools_extrae_JavaProbes_ThreadStartEnd(
10    JNIEnv *env, jclass jc)
11  {
12      Extrae_Java_Probe_ThreadStart_end ();
13  }
14
15  JNIEXPORT void JNICALL
16  Java_es_bsc_cepbatools_extrae_JavaProbes_ObjectNotifyBegin(
17    JNIEnv *env, jclass jc)
18  {
19      Extrae_Java_Probe_ObjectNotify_begin ();
20  }
21
22  JNIEXPORT void JNICALL
23  Java_es_bsc_cepbatools_extrae_JavaProbes_ObjectNotifyEnd(
24    JNIEnv *env, jclass jc)
25  {
26      Extrae_Java_Probe_ObjectNotify_end ();
27  }
```

The probes are implemented as in subsection 4.5.2, in the same file (Code 5.6). Notice how the Thread Start event checks for the pthread tracing activity, while the Object Notify event does not. In this way, Extrae can trace the notification events even during the pthread tracing (as it was already happening for all the events except from the Thread Running one).

Code 5.6: The new probes implemented in `java_probe.c`

```
 1  void Extrae_Java_Probe_ThreadStart_begin(void)
 2  {
 3    if(!EXTRAE_ON() || !EXTRAE_INITIALIZED() ||
 4      Extrae_get_pthread_tracing()) return;
 5    TRACE_MISCEVENTANDCOUNTERS(TIME, JAVA_THREAD_START_EV, EVT_BEGIN,
 6                    EMPTY);
 7  }
 8
 9  void Extrae_Java_Probe_ThreadStart_end(void)
10  {
11    if(!EXTRAE_ON() || !EXTRAE_INITIALIZED() ||
12      Extrae_get_pthread_tracing()) return;
13    TRACE_MISCEVENTANDCOUNTERS(TIME, JAVA_THREAD_START_EV, EVT_END,
14                    EMPTY);
15  }
16
```

```
17  void Extrae_Java_Probe_ObjectNotify_begin(void)
18  {
19      if (!EXTRAE_ON() || !EXTRAE_INITIALIZED()) return;
20
21      TRACE_MISCEVENTANDCOUNTERS(TIME, JAVA_OBJECT_NOTIFY_EV, EVT_BEGIN,
22                          EMPTY);
23  }
24
25
26  void Extrae_Java_Probe_ObjectNotify_end(void)
27  {
28      if (!EXTRAE_ON() || !EXTRAE_INITIALIZED()) return;
29
30      TRACE_MISCEVENTANDCOUNTERS(TIME, JAVA_OBJECT_NOTIFY_EV, EVT_END,
31                          EMPTY);
32  }
```

After that, it is necessary to specify which states they trace. As already said, the state related to the `Thread.start()` method is of the type "Scheduling and Fork/Join", while the state related to `Object.notify()` will be one that has not been mentioned yet: "Group Communication". Once that everything is set, the only remaining step is to call the probes and let the tracing happen.

5.2.4 Instrumentation aspects implementation

Implementing the Aspect is quite straight forward. It is necessary to define two pointcuts to catch the two methods. Moreover, some care is needed in order to avoid some inconveniences. Since the class `Object` is being instrumented, and since all the classes are sub-classes of it, it must be told AspectJ that the events within the Aspect execution must not be included in the pointcut itself. The code looks like Code 5.7.

Code 5.7: `Extrae.aj`: aspect implementation to call the probes before and after the instrumented methods

```
1   package extrae.aspects;
2
3   import org.aspectj.lang.reflect.*;
4   import java.lang.*;
5
6   public aspect Extrae {
7       // !within to avoid inner objects instrumentation
8       pointcut Tread_Create(): !within(extrae.aspects.Extrae)
9                          && call (* java.lang.Thread.start (..));
10
11      pointcut Notify(): !within(extrae.aspects.Extrae)
12                          && call (* java.lang.Object.notify (..));
```

```
13
14      before ( )  :  Tread_Create ( )
15      {
16          es . bsc . cepbatools . extrae . JavaProbes . ThreadStartBegin ( ) ;
17      }
18
19      after ( )  returning  ( )  :  Tread_Create ( )
20      {
21          es . bsc . cepbatools . extrae . JavaProbes . ThreadStartEnd ( ) ;
22      }
23
24      before ( )  :  Notify ( )
25      {
26          es . bsc . cepbatools . extrae . JavaProbes . ObjectNotifyBegin ( ) ;
27      }
28
29      after ( )  returning  ( )  :  Notify ( )
30      {
31          es . bsc . cepbatools . extrae . JavaProbes . ObjectNotifyEnd ( ) ;
32      }
33  }
```

In order to be available for all the executions in Java, all the aspects are placed in a specific system directory during the installation. The chosen directory is `${EXTRAE_LIB_DIR}/extraejaspects`.

5.2.5   Compiling everything and setting the agent

The aspects can be combined to the actual Java program with an operation called "Weaving". This can be delivered in three different ways:

- Compile-time weaving, consisting in compiling the Java and AspectJ source codes together;

- Post-compile weaving (also sometimes called binary weaving), used with existing class or JAR files, that are already compiled in bytecodes;

- Load-time weaving (LTW), that expects to defer the binary weaving until a class loader loads a class file and defines the class to the JVM.

The simplest ones are the first two, while the latter requires some additional settings and precautions. The one used for the User functions (subsection 2.6.2) is the second one, and so the proposed solution will use the "Post-compile weaving" as well. The compilation with AspectJ needs to be done using AspectJ's own compiler, named `ajc`. It is a command similar to `javac`, and takes some option to define the source code (aspects file) and the input classes to instrument.

The AspectJ compiler `ajc` needs to have in the class path all the classes to weave[5]. It will then output the new compiled classes, which will be the ones executed to gather the traces. Input and output files will all be collected in a temporary directory: the aspects will be copied inside `<temp_directory>/aspects` and the instrumented classes will be placed inside `<temp_directory>/instrumented`. All these operations are summarized in Figure 5.1.
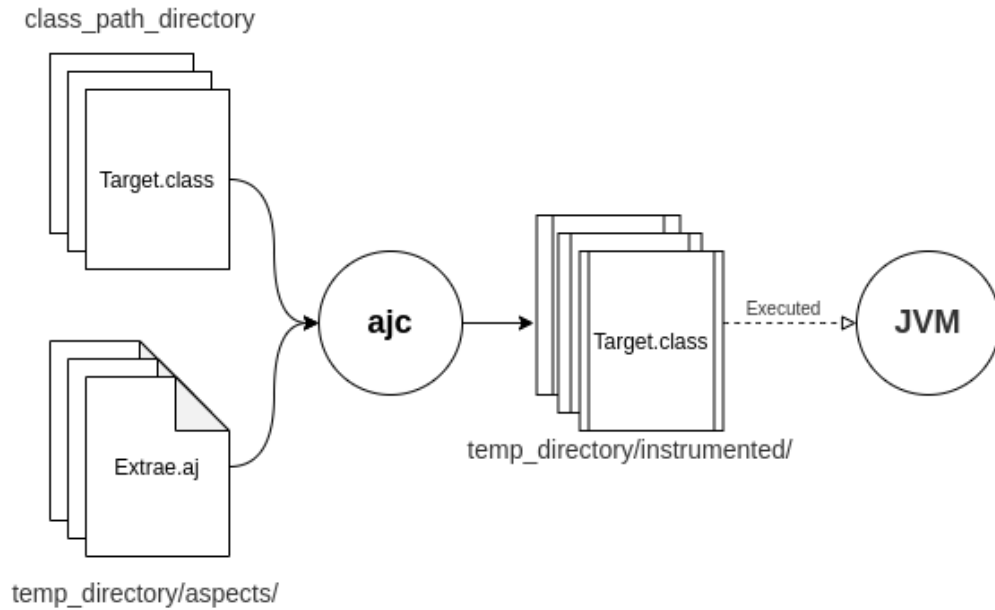
Figure 5.1: Instrumentation process using AspectJ compilation

The compilation is going to be implemented inside `extraej` (Code 5.8), just before launching the java application.

Code 5.8: Extract of `extraej`, containing the aspects compilation

```
tmpdir='mktemp −d extraej.XXXXXX'
mkdir ${tmpdir}/aspects

if [[ "${user_cp}" != "" ]]; then
  inpath=${user_cp}
else
  inpath=.
fi
```

---

[5]For now, this does not represent a problem, since the instrumented classes are part of the standard Java language. However, when the classes will be some external frameworks, some care will be needed when compiling.

```
cp −r ${EXTRAEJ_ASPECTS_DIR}/∗ ${tmpdir}/aspects/

CLASSPATH=${ASPECTJRT_JAR}:${ASPECTWEAVER_JAR}:${
    EXTRAEJ_JAVATRACE_PATH}:${CLASSPATH} \
${AJC} \
  −1.8 \
 −inpath ${inpath} \
 −sourceroots ${tmpdir}/aspects \
 −d ${tmpdir}/instrumented
```

And then, launching the application will be done by adding the directory with the in-strumented classes `<temp_dir>/instrumented` to the class path[6] (Code 5.9).

Code 5.9: Extract of `extraej`, containing the Java launching instruction

```
execute_java ${tmpdir}/instrumented:${ASPECTJRT_JAR}:
    ${ASPECTWEAVER_JAR}:${CLASSPATH} \
    ${EXTRAEJ_LIBPTTRACE_PATH} \
    "$@"
```

All these operations do not alter the original command of execution (the "user class path" option is not needed, because the instrumentation is on the classes `Thread` and `Object`, which are part of the JDK).

5.2.6 Resulting traces and discussion

To show the new implemented features, a new example Java program has been instrumented (Figure 5.2).

Without looking at the code, but zooming on the main part (Figure 5.3), the behaviour of the application can almost be understood with just looking at the traces. The main thread generates the other two (because no scheduling is present on the other threads), `Thread-0` waits until `Thread-1` notifies something, and then, after some operations, they both die and the program ends (also, the main thread was waiting for both without doing anything else).

5.3 Events values: a better view

Using Paraver to show the states was enough to understand the program behaviour, but what about the specific operations? Understanding that a "Group communication" is related to an `Object.notify()` call, or that the "Synchronization"

---

[6]The first argument of `execute_java` represents the class path (section 2.7, Code 2.8).
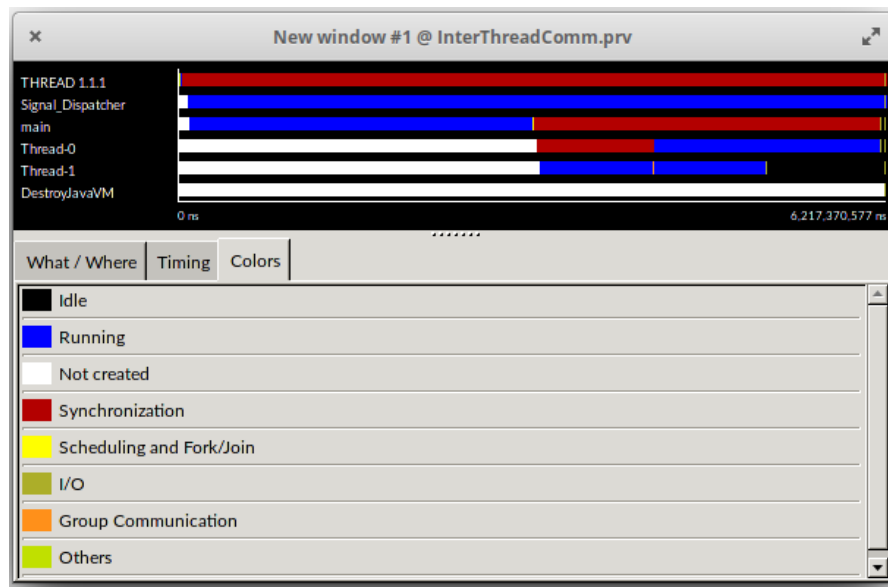
Figure 5.2: Traces of an instrumented application, with the new traced states: Scheduling and Group Communication
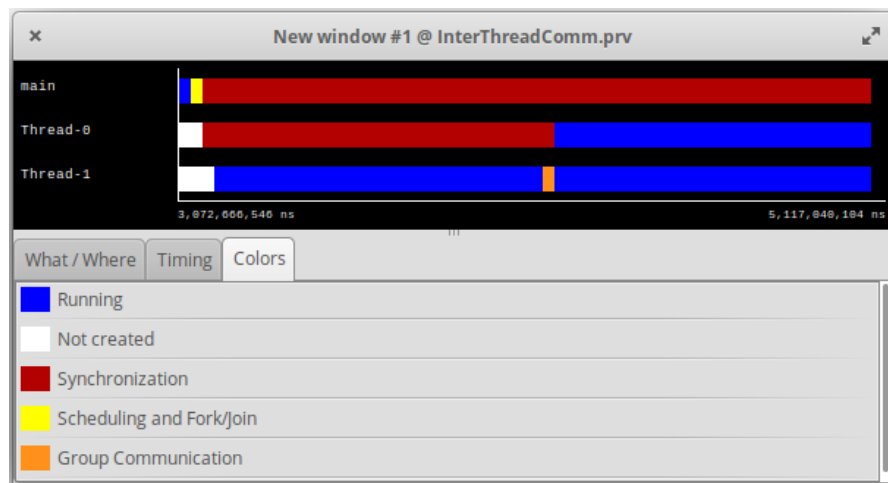
Figure 5.3: Traces of an instrumented application, focus on the main part. It can be noticed the scheduling state on the main thread, while it is generating `Thread-0` and `Thread-1`, and also the notification event on `Thread-1` that "unlocks" `Thread-0` from the waiting state.

state is related to `Object.wait()`, requires a level of knowledge of the Extrae's instrumentation package implementation. Moreover, no clue is given about the "Others" state, or if more events are related to the same state, making them the

same from the point of view of the state. This may not be a problem, if just a general understanding of the program is the finale objective. However, it's inevitably a loss of information that can (and should) be fixed.

Fortunately, Paraver is able to show different events with different colors. The problem is that it bases this differentiation on the value of the event, and not the type. More specifically, all the events traced so far reported all the same values when traced: `EVT_BEGIN` and `EVT_END` (Code 4.12, Code 5.6). For this reason, Paraver would not be able to distinguish among the different events.

In order to show the Java events in different colors, an addition to the Paraver merger[7] has been made. When tracing the event, it is mapped to a different pair type-value. The mapping is shown in Table 5.1[8].

Extrae event type	New type	New value	Event label
`JAVA_GARBAGE_COLLECTOR_EV`	`JAVA_BASE_EV`	1	Garbage Collection
`JAVA_EXCEPTION_EV`	`JAVA_BASE_EV`	2	Exception
`JAVA_OBJECT_ALLOC_EV`	`JAVA_BASE_EV`	3	Object allocated
`JAVA_OBJECT_FREE_EV`	`JAVA_BASE_EV`	4	Object freed
`JAVA_WAIT_EV`	`JAVA_BASE_EV`	5	Monitor wait
`JAVA_THREAD_START_EV`	`JAVA_BASE_EV`	6	Thread scheduling
`JAVA_OBJECT_NOTIFY_EV`	`JAVA_BASE_EV`	7	Monitor notify
All the events with value 0	-	0	Outside Java events

Table 5.1: Events values mapping for Paraver. Valid for `EVT_BEGIN` only, when the original event value is `EVT_END` (that is 0) the new event value will be 0.

The mapping is simply implemented as an array of normal C `struct`s, that is iterated if the event is of one the Java ones. In addition to the mapping, Paraver requires the configuration to be print on the `.pcf` file, in order to associate the event values to the labels. The implementations of the mapping (Code 5.10) and the printing of the labels configuration for the `.pcf` file (Code 5.11), are both in the `merger/paraver/java_prv_events.c` file.

---

[7]The Paraver merger has been introduced in subsection 4.5.4, when talking about the states semantics).

[8]On the table it can be seen how the event `JAVA_THREAD_RUNNING_EV` is not being mapped to a new event type. The reason behind the choice is based on the fact that it would have made the trace more confusing then how it would have added value. In this way, the focus can be on the single operations. Understanding when a thread is generated can be done thanks to the `Thread.start()` event. In any case, Paraver allows to add it to the filter in order to show it together with the other events.

Code 5.10: Extract of the file `java_prv_events.c`, mapping

```
void Translate_JAVA_MPIT2PRV (int typempit, UINT64 valuempit, int *
    typeprv, UINT64 *valueprv)
{
  int index = find_event_mpit(typempit);

  if (index >= 0)
  {   // if found the mapping, change with new type and value
    *typeprv = event_mpit2prv[index].type_prv;
    *valueprv = (valuempit!=0)?event_mpit2prv[index].val_prv:0;
  }
  else
  {   // otherwise, keep the input ones
    *typeprv = typempit;
    *valueprv = valuempit;
  }
}
```

Code 5.11: Extract of the file `java_prv_events.c`, printing the labels

```
void JavaEvent_WriteEnabledOperations (FILE * fd)
{
  int atleastone = FALSE;
  for (unsigned i=0; i < MAX_JAVA_INDEX && !atleastone; i++)
    atleastone |= event_mpit2prv[i].in_use;
  if (!atleastone) return; // if none is used, don't print anything
    and return

  fprintf (fd, "EVENT_TYPE\n");
  fprintf (fd, "0 %d Java basic events", JAVA_BASE_EV);
  fprintf (fd, "VALUES");

  fprintf (fd, "0 Outside thread execution\n");
  for (unsigned i=0; i < MAX_JAVA_INDEX; i++)
  {
    if (event_mpit2prv[i].in_use) // if used in the trace, print
    value and label
      fprintf(fd, "%d %s\n", event_mpit2prv[i].val_prv,
    event_mpit2prv[i].label);
  }
}
```

The translation function is then called by the `trace_paraver_event` function, which is the one that actually prints the numeric values on the trace (Code 5.12).

Code 5.12: Extract of the file `paraver_generator.c`, `trace_paraver_event` function

```c
void trace_paraver_event (
    unsigned int cpu, unsigned int ptask, unsigned int task,
    unsigned int thread, unsigned long long time, unsigned int type,
    UINT64 value)
{
    ...
    if (type >= MPI_MIN_EV && type <= MPI_MAX_EV)
    {
      Translate_MPI_MPIT2PRV (type, value, &tipus, &valor);
    }
    else if (type >= JAVA_MIN_EV && type <= JAVA_MAX_EV) /* if a Java
    event */
    {
      Translate_JAVA_MPIT2PRV (type, value, &tipus, &valor); /* change
    to new type and value */
    }
    else
    {
      tipus = type;
      valor = value;
    }
    ...
}
```

By instrumenting using this implementation, and by changing the view of Paraver in order to filter by the `JAVA_BASE_EV`, the result for the traces are shown in Figure 5.4 (the PiExample program from chapter 2) and Figure 5.5 (the new example program of subsection 5.2.6)[9].

Using this view, together with the state view, will give an holistic understanding of the traced events for all the Java applications. This and the other improvements contained in this chapter will give an additional support for analyzing a real world case study, which is going to be the topic of the next chapter.

---

[9]This configuration can be saved thanks to the Paraver configuration files (with extension `.cfg`). The configuration file for this specific view is reported in Appendix B.
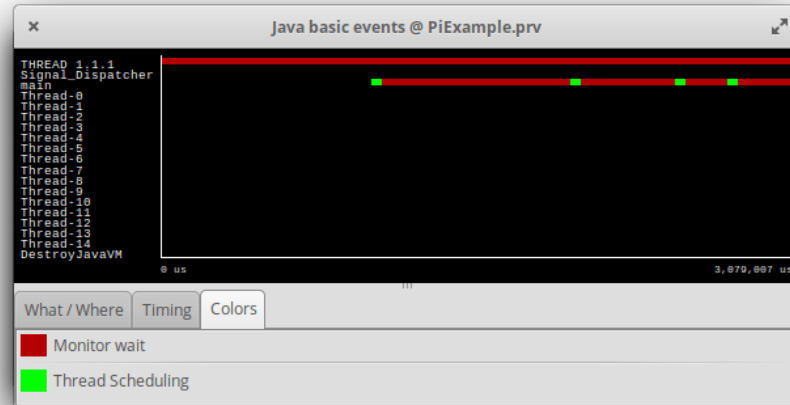
Figure 5.4: PiExample trace with the Java Paraver view
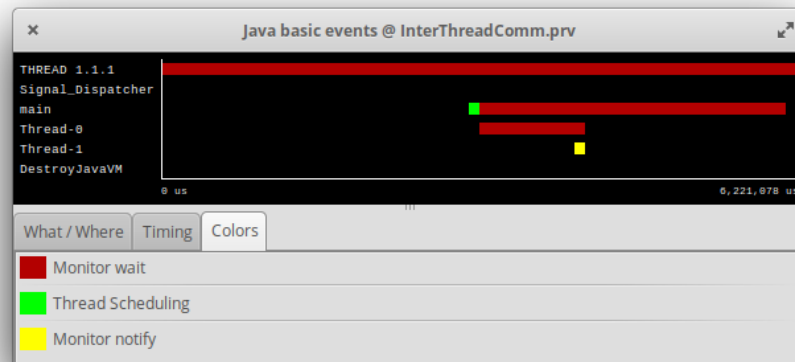
Figure 5.5: New example trace with the Java Paraver view

Chapter 6

Applications and Discussion

The next step in the study, after having developed a baseline tracing platform, would be to apply it to a real application. This chapter covers the application to two of the most famous Java frameworks for distributed computations: Hadoop and Spark.

It follows some discussion on the resulting traces, on the methodology to follow to instrument them and on the implications of the choices made in the previous chapters.

6.1 Analyzing Hadoop MapReduce

Hadoop was introduced in chapter 1 as an important framework implementing the map-reduce paradigm, on which AI applications rely to go distributed (like Weka or Apache Mahout, but also Spark is related to it). In this context, it is now being tested in a non-distributed environment, and so on a single JVM. The application is expected to generate some threads.

6.1.1 The example program

The application that is going to be tested is a Word Count program, a standard example when coming to applications based on the map-reduce framework. It expects the mappers to split their portion in all the words they find and count them, and the reducers to collect all the words of the same kind and merge the related mappers' counts. An explanation of the process is shown in Figure 6.1.
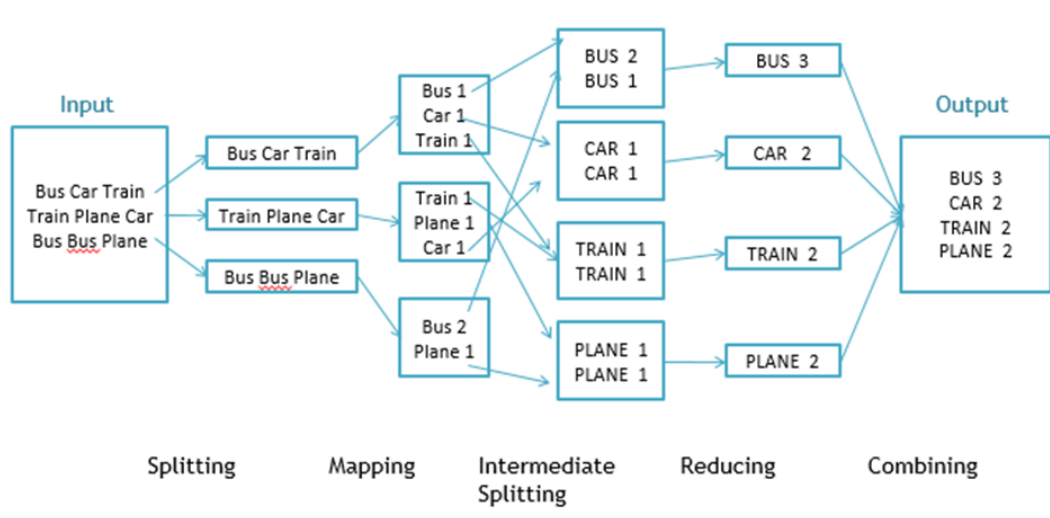
Figure 6.1: Word Count map-reduce application workflow (image from DZone [34])

The specific code is shown in Code 6.1.

Code 6.1: Hadoop WordCount example program

```java
import java.util.StringTokenizer;
import org.apache.hadoop.conf.Configuration;
import org.apache.hadoop.fs.Path;
import org.apache.hadoop.io.*;
import org.apache.hadoop.mapreduce.*;
import org.apache.hadoop.mapreduce.lib.input.FileInputFormat;
import org.apache.hadoop.mapreduce.lib.output.FileOutputFormat;
import org.apache.hadoop.util.GenericOptionsParser;

public class WordCount {

  public static class TokenizerMapper
    extends Mapper<Object, Text, Text, IntWritable>{

      private final static IntWritable one = new IntWritable(1);
      private Text word = new Text();

      public void map(Object key, Text value, Context context
                      ) throws IOException, InterruptedException {
        StringTokenizer itr = new StringTokenizer(value.toString());
        while (itr.hasMoreTokens()) {
          word.set(itr.nextToken());
          context.write(word, one);
        }
      }
    }
```

```
27
28    public static class IntSumReducer
29      extends Reducer<Text,IntWritable,Text,IntWritable> {
30        private IntWritable result = new IntWritable();
31
32        public void reduce(Text key, Iterable<IntWritable> values,
33                           Context context
34                        ) throws IOException, InterruptedException {
35          int sum = 0;
36          for (IntWritable val : values) sum += val.get();
37
38          result.set(sum);
39          context.write(key, result);
40        }
41      }
42
43    public static void main(String[] args) throws Exception {
44      Configuration conf = new Configuration();
45      Job job = new Job(conf, "word count");
46      job.setJarByClass(WordCount.class);
47      job.setMapperClass(TokenizerMapper.class);
48      job.setCombinerClass(IntSumReducer.class);
49      job.setReducerClass(IntSumReducer.class);
50      job.setOutputKeyClass(Text.class);
51      job.setOutputValueClass(IntWritable.class);
52      FileInputFormat.addInputPath(job, new Path("input.txt"));
53      FileOutputFormat.setOutputPath(job, new Path("output"));
54      System.exit(job.waitForCompletion(true) ? 0 : 1);
55    }
56 }
```

6.1.2 Resulting Traces

The program has been analyzed as in previous chapters[1], obtaining the traces shown in Figure 6.2.

The only traced java events, in addition to the thread notification, are the Monitor Wait event and the Exception event (Figure 6.3). The threads names can give some clues on the threads objectives, but it is difficult to understand what it is going on without having more states. This was expected, since the methodology expects to trace specific frameworks-related events.

---

[1]Important! Hadoop dependencies must be specified in the class path:

    extraej -cp <path_to_hadoop_jars> -- WordCount

Maven [35] has been used for the dependecies and the `pom.xml` is reported in Appendix B.
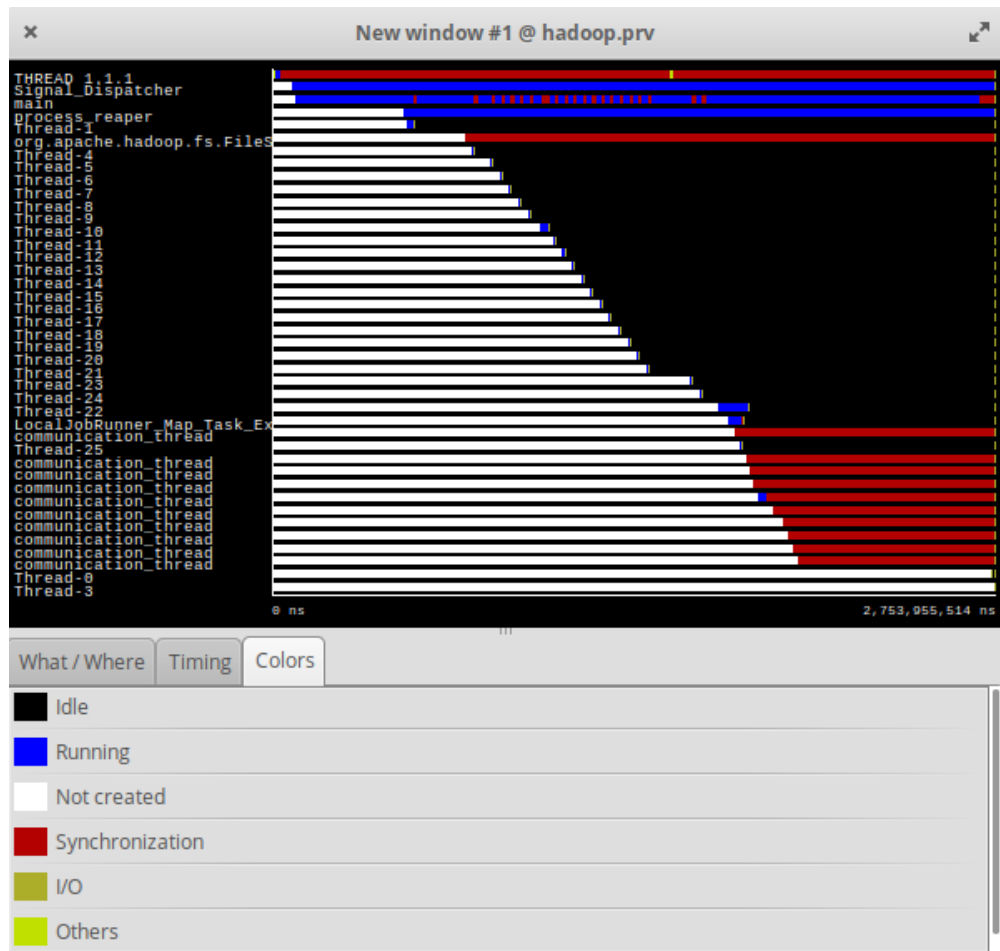
Figure 6.2: Hadoop execution states traces

6.1.3   Probes-Application interference

Unfortunately, obtaining traces for a complete execution was not possible, due to
a strange behaviour of the application. Indeed, it appeared to stop prematurely,
without even generating the final output. Without the Extrae instrumentation
(that is, without using the linker preload and the JVM TI agent), the execution
ends normally. As soon as Extrae does something, any application using Hadoop
MapReduce stops before the mapping step, without raising any error or exception
that may give any clue about the problem. This aspect needed more time to
be investigated properly, because the reasons behind this behaviour remained
unexplained.
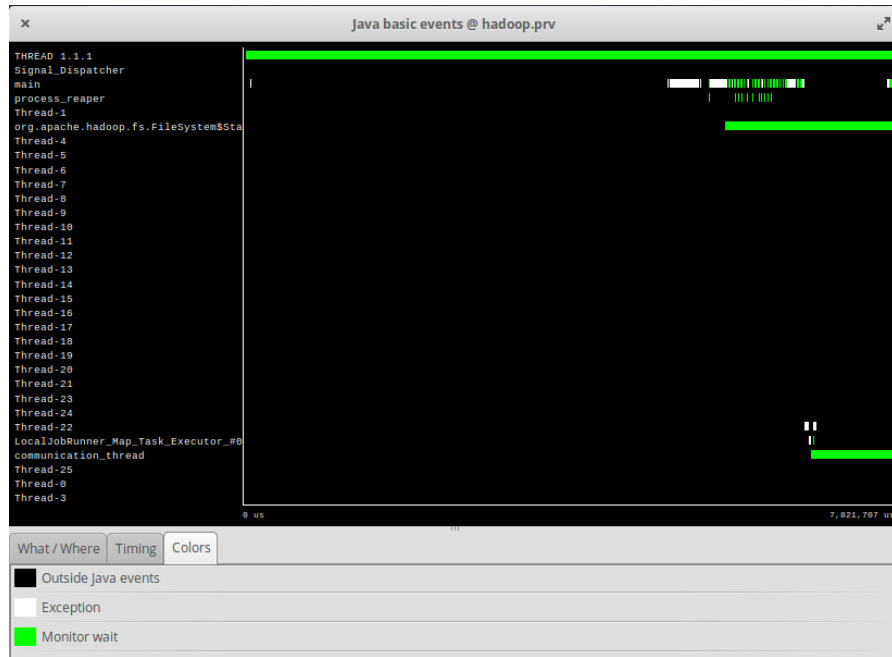
Figure 6.3: Hadoop execution Java events traces

6.1.4 Steps towards instrumentation

In order to understand the new methods to instrument and associate them to specific events, an operation that can be performed is profiling with some Java profiling tool. In this specific case, IntelliJ's "CPU profiling" tool has been employed [36].

The result of this analysis brought a list of interesting functions to instrument. A good criteria to look at which functions are more interesting to trace, is by looking at the number of samples in which they were being executed[2]. By following this approach, the interesting functions will be detected.

The functions contained in the main file (`WordCount$TokenizerMapper.map` and `WordCount$IntSumReducer.reducer`) can also be instrumented, in order to know on which threads they are being called, helping to understand which threads are mappers and which are reducers. Moreover, from the profiling output (Figure 6.4), it can be seen the under the cover frameworks used for implementing the map-reduce features: `FutureTask`s and `ThreadPool`s. Both of them are Java basic classes, not related to Hadoop, that can be instrumented in order to give information on every

---

[2]A profiler normally works with some sampling mechanism, by reporting the function being executed at each sample.

Java application that use them, not just the ones based on Hadoop.
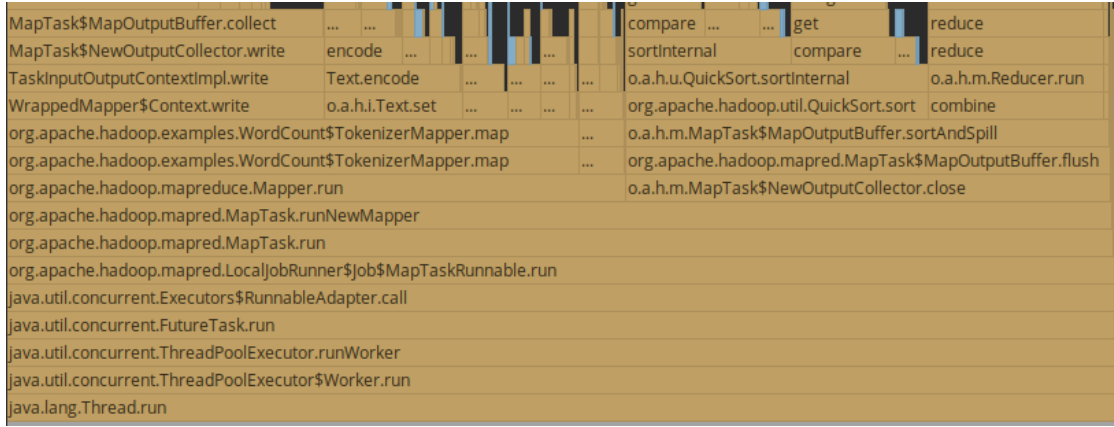
Figure 6.4: IntelliJ CPU profiler output for Hadoop WordCount program. It should be read from bottom to top, considering that each function is the caller on the one on top of it. The wider the function area is, the more it has been detected in the samples.

These various methods can be instrumented with the methodologies exposed in this thesis. Specifically, AspectJ should be used to catch them and defining the pieces of advice (Code 6.2). Specific events should be prepared, traced and "interpreted" from the state point of view. However, this work, applicable to all the kinds of frameworks, is left as a further improvement.

Code 6.2: An example of how mappers and reducers methods can be instrumented and traced. The interesting part is the "+" operator, that lets to catch methods inherited by other classes. Its utility is based on the fact that mappers and reducers—in Hadoop—must extend two specific Hadoop classes: `Mapper` and `Reducer`.

```
public aspect HadoopMapReduceInstrumentation {
    pointcut      MapperExecution() : call (void org.apache.hadoop.
    mapreduce.Mapper+.map (..));
    before() : MapperExecution()
            {
                es.bsc.cepbatools.extrae.JavaProbes.MapperBegin();
            }
    after() returning () : MapperExecution ()
            {
                es.bsc.cepbatools.extrae.JavaProbes.MapperEnd();
            }

    pointcut      ReducerExecution() : call (void org.apache.hadoop.
    mapreduce.Reducer+.reduce (..));
    before() : ReducerExecution()
```

```
14                      {
15                              es.bsc.cepbatools.extrae.JavaProbes.ReducerBegin();
16                      }
17      after() returning () : ReducerExecution ()
18                      {
19                              es.bsc.cepbatools.extrae.JavaProbes.ReducerEnd();
20                      }
21 }
```

6.2   Analyzing Spark

Spark was introduced in chapter 1 as well, and it is another distributed platform like Hadoop. As in the previous analysis, Spark is going to be tested in a non-distributed environment, and so on a single JVM that will generate some threads.

6.2.1   The example program

The example program is again a word counter, as in the previous analysis. The concept behind the execution is very similar, but the implementation with Spark is much more straight-forward (thanks to the RDD abstraction).

Code 6.3: WordCount program implemented using Spark

```
1  import org.apache.spark.SparkConf;
2  import org.apache.spark.api.java.JavaPairRDD;
3  import org.apache.spark.api.java.JavaRDD;
4  import org.apache.spark.api.java.JavaSparkContext;
5  import scala.Tuple2;
6
7  import java.util.Arrays;
8
9  public class WordCounter {
10     private static void wordCount(String fileName) {
11         SparkConf sparkConf = new SparkConf().setMaster("local").
    setAppName("JD Word Counter");
12         JavaSparkContext sparkContext = new JavaSparkContext(
    sparkConf);
13         JavaRDD<String> inputFile = sparkContext.textFile(fileName);
14         JavaRDD<String> wordsFromFile = inputFile.flatMap(l -> Arrays
    .asList(l.split(" ")).iterator());
15         JavaPairRDD countData = wordsFromFile.mapToPair(t -> new
    Tuple2(t, 1)).reduceByKey((x, y) -> (int) x + (int) y);
16         countData.saveAsTextFile("output");
17     }
18
19     public static void main(String[] args) {
```

```
20        String  fileName = "input.txt";
21        wordCount(fileName);
22    }
23 }
```

6.2.2   Resulting traces
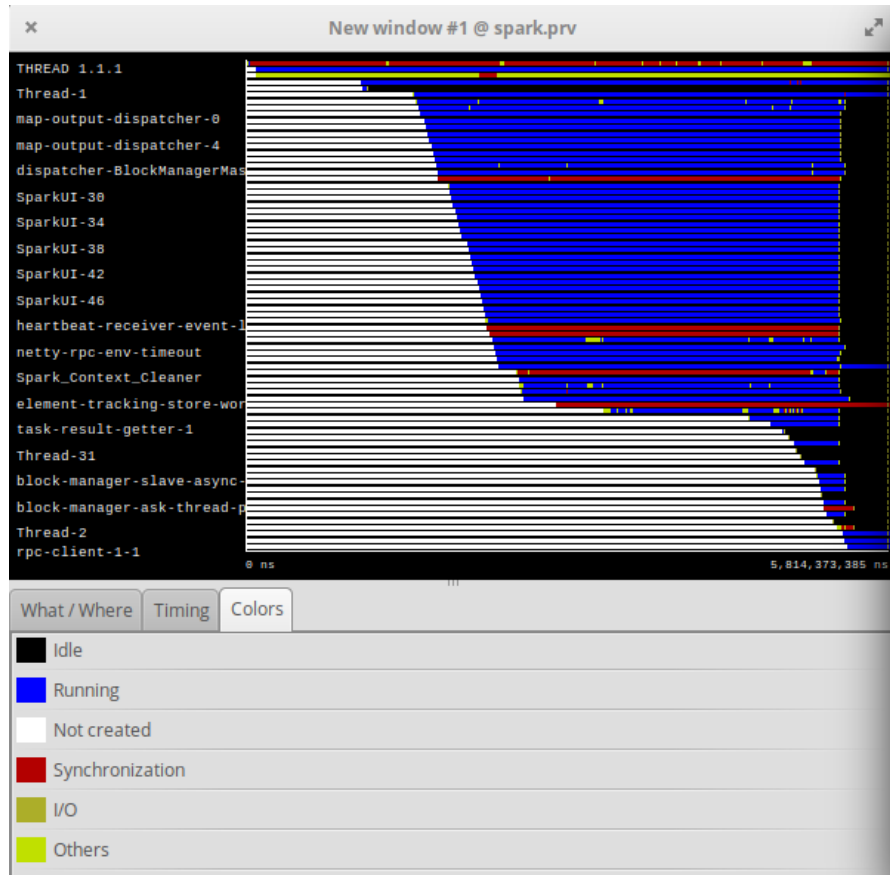
Figure 6.5: Spark execution traces: Application States

The resulting traces present the Monitor Waiting, the Exception and the Garbage Collection events (Figure 6.6). There are many threads, each one of them with a specific name that explain their purpose (Figure 6.5). For example, there are some called "map-output-dispatcher", which clearly refer to the mapping step of the data. Others are called "task-result-getter" or "shuffle-client", which again are relatable with the MapReduce steps. In this case, as opposed to the Hadoop analysis, the name of the threads appears to be one of the most important information to get the general behaviour of the program.
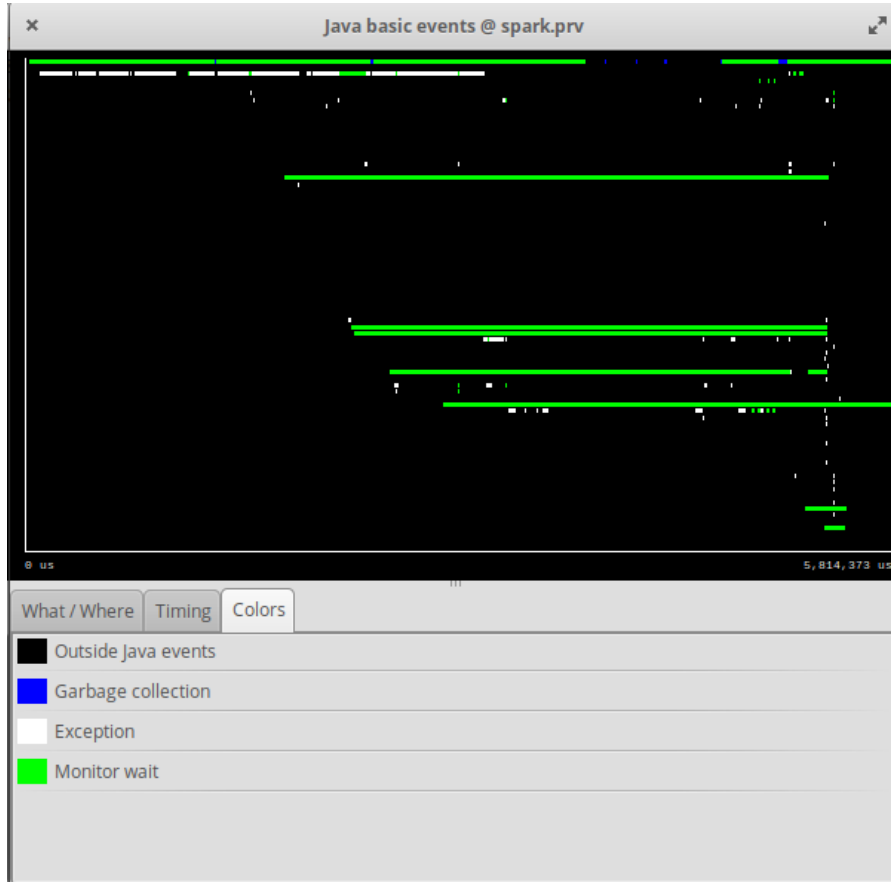
Figure 6.6: Spark execution traces: Java Events. On top of the Exception and Waiting events, on the top thread it can be seen the Garbage Collection event happening.

6.2.3   Instrumentation overhead

Instrumenting implies some overhead, which for this Spark execution has been measured. This has been calculated by taking the lowest value of 10 distinct executions[3], all running with a 700MB example input file. Moreover, the data have been purified from the initialization time of Extrae, JVM and Spark[4]. The data are reported in Table 6.1.

---

[3]It has been taken the lowest because the execution is always the same, the only differences can just be introduced by OS scheduling and interrupts, which are not interesting.

[4]The JVM and Spark initialization can be subjected to instrumentation as well, but it would be a constant value in any case, which does not change among different applications. For this reason, they can be neglected.

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Test	Total time	Init time	Purified time	Overhead
Non-instrumented	4.538s	2.338s	2.200s	1x
Instrumented	7.344s	4.634s	2.710s	1.232x

Table 6.1: Time taken by instrumented and non-instrumented runs on the Spark example

As it can be seen from Table 6.1, the overhead introduced by the Extrae instrumentation is $\approx 1.23\times$.

6.2.4 Steps toward instrumentation

The steps to instrument the Spark framework are similar to the ones explained previously. In this case, however, it must be pointed out that Spark is written mainly in Scala[5], and not in Java like Hadoop. For this reason, on top of the events raised by the JVM and catched by the JVM TI (that are still available, since Scala runs on the JVM), the implementation of the Aspects should be done in Scala.

Although the compilation cannot be done in the exactly same way, the architecture of the tracing platform would not vary: it would keep expecting the generation of some aspects to instrument compiled classes, either Java or Scala being the programming language originally employed for the implementation.

6.3 Tracing overhead analysis

One interesting data to analyze is the overhead introduced by the tracing activity and the various instrumentation instructions.

In order to understand how the overhead is generated, the time has been taken against different configurations, in order to have information on how much overhead is introduced by each step in the tracing process:

- Without instrumentation: the plain execution, without any agent or preloaded libraries;

---

[5]Scala, already mentioned in chapter 1, is a general-purpose programming language providing support for both object-oriented programming and functional programming. Its source code is intended to be compiled to Java bytecode, so that the resulting executable code runs on a Java virtual machine [37].

- JVM TI only: with just the agent and the related callbacks, but without the calls to the Extrae core functions;

- JVM TI + AspectJ (JNI only): just the agent with the callbacks and the AspectJ pieces of advice, without calling the Extrae core functions;

- JVM TI + Extrae calls: just the agent and Extrae, without AspectJ;

- Complete instrumentation: with the agent, AspectJ and all the calls to the Extrae core functions.

The program that has been tested is a simple generation of threads (Code B.5), that involves both the events generated by the JVM TI and the methods instrumented using AspectJ.

Test	Total time	Init time	Purified time	Overhead
Non-instrumented	1.685s	0.660s	1.025s	1x
JVM TI only	1.810s	0.741s	1.069s	1.043x
JVM TI + AspectJ (JNI only)	2.079s	0.994s	1.085s	1.059x
JVM TI + Extrae calls	2.180s	0.817s	1.363s	1.330x
Complete instrumentation	2.491s	1.063s	1.428s	1.393x

Table 6.2: Resulting time measurements from tracing overhead analysis. Graphically depicted in Figure 6.7

6.4   Discussion

Thread identification

During these applications, the issue of thread identification can be discussed again. The threads looked too many, and they could probably be reduced to less threads.

However, in the case of Hadoop, if the events of being "mappers" or "reducers" are traced, the problem of using "the same space" for the threads that do different things is not a problem anymore, because an "Hadoop" view would show these events in different colors and would make it clear what each thread is up to at any given time. Moreover, also the threads names are most of the times in the form "`Thread 1.1.x`", so not really explicative of the final purpose of the thread itself, which is another reason for which the "separation of spaces", in this case, would not sacrifice any valuable information.

On the contrary, with Spark the names of the threads were much more important,

because they could identify the main operations of a thread without even tracing new events.

A conclusion that can be made is that leaving one thread identification system for all the cases is not the best choice. It should be allowed to decide based on the applications, maybe through an Extrae option in the XML configuration file.

Overhead

The overhead introduced by Extrae does not look so important. For Spark it has been $\approx 1.23\times$, but it must be taken into account that for now the instrumentation is still basic. Considering that a whole framework would be instrumented, it can be expected that this overhead will increase further. The extent of this increase cannot be easily predicted.

An idea of how much additional overhead can be reached is given by the analysis in section 6.3, because in that case the program was almost totally instrumented. The overhead resulted to be $\approx 1.39\times$, which can still be considered acceptable. Indeed, looking at tracing from the perspective of a post-mortem program analysis (instead of continuous monitoring), the overheads result normally acceptable if they give valuable information to trace.
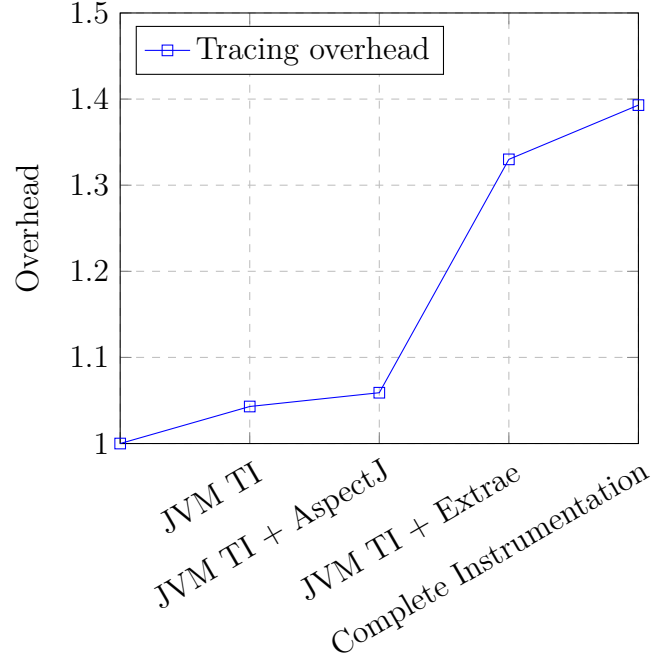
Figure 6.7: Overhead generated by the different mechanisms used to trace the events. Data taken from Table 6.2

Moreover, as it can be seen from Figure 6.7, the overhead is mainly generated by the Extrae calls. Thanks to this information, it can be safely asserted that the mechanisms used to call the Extrae core functions are almost negligible for the overall tracing platform, since together they add less then $1.1\times$ overhead.

The findings and the methodology

In this chapter the idea was to instrument Hadoop and gather the valuable information, by applying the methodologies presented through the whole thesis. This could not be finished due to the problems occurred and to lack of time. Indeed, this chapter needs to be taken as a photograph of a partial work.

At the time of writing, the findings given by analyzing Hadoop and Spark with the current state of the work appear to be poor. However, this does not prove that the methodology is not valuable. It could not be applied properly and all the (partial) findings have been reported in this chapter, with no exaggerations, nor belittlements.

Chapter 7

Conclusions

Performance analysis is a powerful tool, especially when considering HPC applications. The entire thesis has been developed by following this principle, which is based on the concept that improvements can be made only when a kind of measurement is available.

Having been developed as an intern at the BSC, this work has been based on Paraver and Extrae, the two tools developed by the Performance Tools department of the institute. More specifically, the focus has been on the latter, which needed to be adapted to trace the right events for Java applications.

The work started with a global understanding of the tools and on the Performance Analysis techniques. By analyzing an example Java program, it could be possible to gather an holistic view of these aspects, included a detailed understanding of the state of the art of Extrae's Java instrumentation features.

The tracing capabilities for Java were poor, but some experimental features gave the right cues to continue the work in specific directions, that resulted to be effective to trace new events. Specifically, the final solution is based on a combination of JVM TI, AspectJ and JNI. The first one is an interface made available by the JVM, while the second one is an extension of the Java programming language to implement aspect-oriented programming in Java program, which has been used together with JNI to interact with the C-implemented Extrae core.

The event-driven tracing, by using the JVM TI, resulted to be effective. It has been so especially because of the nature of the events provided by the JVM TI, since they are specifically designed for similar purposes. Indeed, the JVM TI is thought to be used by custom profilers and debuggers, which have many things in common with Extrae. For this reason, the JVM TI is of undoubtable value for a

good tracing platform that aims to trace Java applications.

Moreover, AspectJ resulted to be very useful to reach the spots that the JVM TI events could not reach. Despite being designed for this applications, the JVM TI was not enough to cover all the possible cases. Extrae usually offers much more detailed instrumentations when `C/C++` programs are under the magnifying glass. JVM TI needed to be aided somehow, and AspectJ delivers this job admirably. It can catch almost any point of the execution, by just knowing which methods to trace (which is an unmissable requirement for any kind of instrumentation, at least in Extrae).

Finally, all the mechanisms mentioned above have a very low overhead. Most of the overhead introduced by the instrumentation has been generated by the calls to Extrae.

7.1   Further improvements

The work in this thesis is not complete and needs certain improvements to be effectively employed to analyze real-world applications.

First of all, as it was explained in chapter 1, most of the Java applications employed in an HPC environment run in distributed (simulated) environment. For this reason, all the work saw in this thesis should also consider the fact of gathering the traces of multiple JVMs, usually running in different software containers, and collect them together.

As a side improvement, which is more like a further investigation, it must be recalled the problems faced during the Hadoop analysis, where the instrumentation was interfering with the application (which is something that must not happen, ever). Any test made on other applications did not generate this problem, but time must be invested to understand the reasons behind this behaviour.

In addition to the distributed tracing, the data on the callers methods can be traced too. In other instrumented frameworks like MPI or OpenMP, callers provide a valuable information during Performance Analysis. Moreover, such feature would be extremely useful when instrumenting new frameworks, because it can basically substitute the profilers in the job of finding new valuable methods to trace.

Moreover, the differentiated threads IDs management that can be activated or deactivated depndending on the target applications, explained in section 6.4, has been left as a further improvement.

Finally, the advanced features of AspectJ can be employed to even further enhance the detail of the events. For example, AspectJ can differentiate between callers,

which in the real world could lead to different kinds of events, like a call to `Object.wait()`, that can be a synchronization event or a join event, depending on which type of object it is called. This was just an example, but AspectJ provides many interesting features that are worthy to be tried out.

7.2 Final considerations

The whole work in this thesis has been done to develop a methodology to follow, in order to extract the information to be traced. That means, despite all the improvements that such platform needs to be claimed as an effective real-world tool, the main focus was on the tools and on how to employ them for tracing purposes, rather than the development of a final product—even if, that one is the final objective and it has been kept clear in mind during the coding phase, trying to operate with all the best practices.

As said also in the last chapter, the applications are still partial and further improved tool is needed. But by following the methods showed throughout the thesis, almost any new framework can be instrumented, with just small code adaptations. The basis are built, they just need to grow and apply to different applications.

Appendix A

Environment set-up

A.1 GitHub

All the files, including source code, scripts and installation files, are stored in a git repository on my personal GitHub account. The link is the following:
`https://github.com/rstagi/thesis`

The repository, inside a sub-folder named "*installation*", contains a git submodule which points to a fork of the original Extrae repository. In the fork repository, under a branch named `javatrace`, there are all the changes that are being made in order to extend Extrae's functionalities for Java.

Moreover, in the root folder there are the *Dockerfile* (reported in Appendix B) for the Docker image and the scripts to build the image and running the applications. Running the application is done inside the Docker container, by using its installed software for the generation and visualization of the traces. To test such scripts, there is an "*examples*" folder with some examples of Java applications, each of them containing a *Makefile* to build and run the example within the container.

Finally, a README file is provided to help in using the scripts and the examples, as well as a folder named "*docs*" which contains two reports and the present thesis.

A.2 Examples of usage

A.2.1 Set-up

To set up the environment, it is necessary to clone the repository together with the submodule. This can be done by running:

```
git clone https://github.com/rstagi/thesis.git --recursive
```

A.2.2 Docker image build

To build the Docker image, it is provided a script named `build_docker_javatrace.sh` which can be found in the root directory of the repository and needs to be run there:

```
./build_docker_javatrace.sh
```

This command will at first clean the Extrae submodule (by running a `git clean` command inside it) and then it will build the Docker image defined with the Dockerfile.

An option `-pull [<target_branch_or_tag>]` can be specified, in order to switch on a different branch. Normally, the submodule will point to the last commit associated with the current commit of the "thesis" repository. By adding this option, the script will switch on the target branch or target if specified, or to `javatrace` if no target has been specified after `-pull`.

The image will be based on OpenSUSE. During the building process, the necessary tools (like compilers, developers libraries, etc.) will be installed, the installation files of Extrae (installed by using the sources), Paraver and AspectJ will be copied inside and used, and finally the image will be tagged as `extrae/javatrace`.

A.2.3 Running the program

To run and trace a Java program, there is the script `run_javatrace.sh`. This can be used in the following way:

```
 run_javatrace.sh  [-R] [-show] [-mvn] [-cp <CLASSPATH>] <target>
```

The `target` can be either a Java class or a jar file. For the former, which was the standard mode in which Extrae used to work with Java programs, the class should be present in the directory where the command is launched or in the classpath. In both cases, all the files in the target's directory will be copied inside the Docker container. The solution is not very elegant, but it's effective and it makes the logic behind the script much easier. For the purposes of the analyzed applications

it's quite enough. The options are not mandatory, and they have the following meaning:

- `-jar`: the target is a jar file

- `-r, -R`: the files will be copied in recursive mode

- `-show`: once the program terminates, it will automatically run Paraver to show the trace

- `-mvn`: to run a maven project with a `pom.xml`

- `-cp`: to specify a custom class path

A.2.4   Show the traces

To show the traces generated by a program, in addition to the `-show` option of the running script, a new script, named `show_trace.sh` is provided:

```
./show_trace.sh <target_prv_file>
```

All the input files are copied inside the container and Paraver is executed to show the file.

A.2.5   Examples

As previously stated, there are some examples in the repository. There are several, but all of them need the Docker to be built first. Moreover, there are the *Makefile*s to help in running the examples using the Docker container. The useful targets are the following:

- `make run`: runs the program inside the container and copies the files in the current directory

- `make runshow`: runs the program as the `run` target and also shows the traces using Paraver

- `make show`: needs to be used after the `run` or `runshow` targets and shows the output trace in Paraver

Appendix B

Useful Code

Code B.1: Environment Dockerfile

```
1 #Based on OpenSUSE Leap
2 FROM opensuse/leap
3
4 #Dependencies
5 RUN zypper install −y gcc gcc−c++ gcc−fortran binutils−devel which
      wget git
6 RUN zypper install −t pattern −y devel_C_C++
7 RUN zypper install −y java java−1_8_0−openjdk java−1_8_0−openjdk−
      devel
8 ENV CLASSPATH /usr/lib64/jvm/java−1.8.0−openjdk−1.8.0/lib/:${
      CLASSPATH}
9 RUN zypper install −y papi papi−devel
10 RUN zypper install −y libxml2 libxml2−devel
11 RUN zypper install −y libunwind−devel
12 RUN zypper install −y gtk2−devel
13 RUN zypper install −y vim
14 RUN zypper install −y bzip2
15 RUN zypper install −y gdb
16
17 #OpenMP
18 RUN zypper install −y libgomp1
19
20 #MPI
21 RUN zypper install −y openmpi openmpi−devel
22
23 #Aspectj
24 RUN cd /tmp && wget http://mirror.dkm.cz/eclipse/tools/aspectj/
      aspectj−1.9.5.jar
25 RUN cd /tmp && java −jar ./aspectj−1.9.5.jar −to /usr/lib64/jvm/java
      −1.8.0−openjdk−1.8.0/
```

```
26
27  #Paraver character set
28  RUN zypper install −y lato−fonts glibc−locale glibc−i18ndata
29  RUN localedef −i en_US −f UTF−8 en_US
30  ENV LANG en_US.UTF−8
31  ENV LANGUAGE en_US:en
32  ENV LC_ALL en_US.UTF−8
33
34  #Paraver
35  RUN cd /tmp && wget ftp.tools.bsc.es/wxparaver/wxparaver−4.8.2−
        Linux_x86_64.tar.bz2
36  RUN cd /tmp && tar xjf wxparaver−4.8.2−Linux_x86_64.tar.bz2 && mv ./
        wxparaver−4.8.2−Linux_x86_64/ /usr/share/wxparaver/
37
38  #Extrae
39  #Uncomment first line and comment second line to clone the original
        Extrae package
40  #RUN cd /tmp && git clone https://github.com/bsc−performance−tools/
        extrae.git && cd extrae
41  RUN cd /tmp && git clone https://github.com/rstagi/extrae.git && cd
        extrae && git checkout javatrace && git pull
42  ENV MPI_ROOT /usr/lib64/mpi/gcc/openmpi
43  RUN cd /tmp/extrae && ./bootstrap && ./configure  −−with−mpi=${
        MPI_ROOT} \
44                                  −−enable−openmp \
45                                  −−without−dyninst \
46                          −−with−papi=/usr \
47                                  −−enable−pthread \
48                                  −−with−java−jdk=/usr/lib64/jvm/java
        −1.8.0−openjdk−1.8.0 \
49                                  −−with−java−aspectj=/usr/lib64/jvm/java
        −1.8.0−openjdk−1.8.0 \
50                                  −−with−unwind=/usr \
51                                  −−without−elf \
52                                  −−with−binary−type=64
53  ENV CC gcc
54  ENV CXX g++
55  ENV MPICC ${MPI_ROOT}/bin/mpicc
56  ENV MPICXX ${MPI_ROOT}/bin/mpicxx
57  RUN cd /tmp/extrae && make −j$(nproc) && make install
58
59  #Cleaning up
60  RUN rm −rf /tmp/*
61
62  #Scripts folder
63  RUN mkdir −p /home/javatraces
64  RUN chmod 666 −R /home/javatraces
65  WORKDIR /home/javatraces
```

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Code B.2: Paraver configuration file for Java: JavaThreads.cfg

```
1  ConfigFile.Version: 3.4
2  ConfigFile.NumWindows: 1
3  ConfigFile.BeginDescription
4  ConfigFile.EndDescription
5
6  < NEW DISPLAYING WINDOW Active garbage collector >
7
8  window_name Java basic events
9  window_type single
10 window_id 1
11 window_position_x 388
12 window_position_y 228
13 window_width 600
14 window_height 115
15 window_comm_lines_enabled false
16 window_flags_enabled false
17 window_noncolor_mode true
18 window_logical_filtered true
19 window_physical_filtered false
20 window_comm_fromto true
21 window_comm_tagsize true
22 window_comm_typeval true
23 window_units Microseconds
24 window_maximum_y 18.000000000000
25 window_minimum_y 0.000000000000
26 window_compute_y_max false
27 window_level thread
28 window_scale_relative 1.000000000000
29 window_end_time_relative 1.000000000000
30 window_object appl { 1, { All } }
31 window_begin_time_relative 0.000000000000
32 window_open true
33 window_drawmode 1
34 window_drawmode_rows 1
35 window_pixel_size 1
36 window_labels_to_draw 1
37 window_selected_functions { 14, { {cpu, Active Thd}, {appl, Adding},
       {task, Adding}, {thread, Last Evt Val}, {node, Adding}, {system,
       Adding}, {workload, Adding}, {from_obj, All}, {to_obj, All}, {
       tag_msg, All}, {size_msg, All}, {bw_msg, All}, {evt_type, =}, {
       evt_value, All} } }
38 window_compose_functions { 9, { {compose_cpu, As Is}, {compose_appl,
       As Is}, {compose_task, As Is}, {compose_thread, As Is}, {
       compose_node, As Is}, {compose_system, As Is}, {compose_workload,
       As Is}, {topcompose1, As Is}, {topcompose2, As Is} } }
39 window_filter_module evt_type 1 48000000
40 window_filter_module evt_type_label 1 "Java basic events"
```

Code B.3: POM file for Hadoop example

```xml
1  <?xml version="1.0" encoding="UTF-8"?>
2  <project xmlns="http://maven.apache.org/POM/4.0.0"
3           xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
4           xsi:schemaLocation="http://maven.apache.org/POM/4.0.0 http:
   //maven.apache.org/xsd/maven-4.0.0.xsd">
5      <modelVersion>4.0.0</modelVersion>
6      <groupId>org.example</groupId>
7      <artifactId>hadooptest</artifactId>
8      <version>1.0-SNAPSHOT</version>
9      <dependencies>
10         <dependency>
11             <groupId>org.apache.hadoop</groupId>
12             <artifactId>hadoop-mapreduce-examples</artifactId>
13             <version>2.7.3</version>
14         </dependency>
15         <dependency>
16             <groupId>org.apache.hadoop</groupId>
17             <artifactId>hadoop-mapreduce-client-common</artifactId>
18             <version>2.7.3</version>
19         </dependency>
20         <dependency>
21             <groupId>org.apache.hadoop</groupId>
22             <artifactId>hadoop-common</artifactId>
23             <version>2.7.3</version>
24         </dependency>
25     </dependencies>
26     <build>
27         <plugins>
28             <plugin>
29                 <groupId>org.apache.maven.plugins</groupId>
30                 <artifactId>maven-jar-plugin</artifactId>
31                 <configuration>
32                     <archive>
33                         <manifest>
34                             <addClasspath>true</addClasspath>
35                             <classpathPrefix>lib/</classpathPrefix>
36                             <mainClass>org.apache.hadoop.examples.
   WordCount</mainClass>
37                         </manifest>
38                     </archive>
39                 </configuration>
40             </plugin>
41             <plugin>
42                 <groupId>org.apache.maven.plugins</groupId>
43                 <artifactId>maven-dependency-plugin</artifactId>
44                 <executions>
45                     <execution>
46                         <id>copy</id>
```

```
47                          <phase>package</phase>
48                          <goals>
49                              <goal>copy−dependencies</goal>
50                          </goals>
51                          <configuration>
52                              <outputDirectory>${project.build.
     directory}/lib</outputDirectory>
53                          </configuration>
54                      </execution>
55                  </executions>
56              </plugin>
57              <plugin>
58                  <artifactId>maven−assembly−plugin</artifactId>
59                  <configuration>
60                      <archive>
61                          <manifest>
62                              <mainClass>org.apache.hadoop.examples.
     WordCount</mainClass>
63                          </manifest>
64                      </archive>
65                      <descriptorRefs>
66                          <descriptorRef>jar−with−dependencies</
     descriptorRef>
67                      </descriptorRefs>
68                  </configuration>
69              </plugin>
70
71              <plugin>
72                  <groupId>org.apache.maven.plugins</groupId>
73                  <artifactId>maven−compiler−plugin</artifactId>
74                  <version>3.6.1</version>
75                  <configuration>
76                  <source>1.8</source>
77                  <target>1.8</target>
78                  </configuration>
79              </plugin>
80          </plugins>
81      </build>
82 </project>
```

Code B.4: POM file for Spark example

```xml
<?xml version="1.0" encoding="UTF-8"?>
<project xmlns="http://maven.apache.org/POM/4.0.0"
         xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
         xsi:schemaLocation="http://maven.apache.org/POM/4.0.0 http:
    //maven.apache.org/xsd/maven-4.0.0.xsd">
    <modelVersion>4.0.0</modelVersion>


    <groupId>org.example</groupId>
    <artifactId>sparktestmvn</artifactId>
    <version>1.0-SNAPSHOT</version>



    <dependencies>
        <!-- https://mvnrepository.com/artifact/org.apache.spark/
    spark-core -->
        <dependency>
            <groupId>org.apache.spark</groupId>
            <artifactId>spark-core_2.12</artifactId>
            <version>3.0.0-preview2</version>
        </dependency>

        <dependency>
            <groupId>junit</groupId>
            <artifactId>junit</artifactId>
            <version>4.11</version>
            <scope>test</scope>
        </dependency>
    </dependencies>

    <build>
        <plugins>
            <plugin>
                <groupId>org.apache.maven.plugins</groupId>
                <artifactId>maven-compiler-plugin</artifactId>
                <version>2.0.2</version>
                <configuration>
                    <source>1.8</source>
                    <target>1.8</target>
                </configuration>
            </plugin>
            <plugin>
                <groupId>org.apache.maven.plugins</groupId>
                <artifactId>maven-jar-plugin</artifactId>
                <configuration>
                    <archive>
                        <manifest>
                            <addClasspath>true</addClasspath>
                            <classpathPrefix>lib/</classpathPrefix>
```

```
47                          <mainClass>com.journaldev.sparkdemo.
    WordCounter</mainClass>
48                      </manifest>
49                  </archive>
50              </configuration>
51          </plugin>
52          <plugin>
53              <groupId>org.apache.maven.plugins</groupId>
54              <artifactId>maven-dependency-plugin</artifactId>
55              <executions>
56                  <execution>
57                      <id>copy</id>
58                      <phase>package</phase>
59                      <goals>
60                          <goal>copy-dependencies</goal>
61                      </goals>
62                      <configuration>
63                          <outputDirectory>${project.build.
    directory}/lib</outputDirectory>
64                      </configuration>
65                  </execution>
66              </executions>
67          </plugin>
68      </plugins>
69  </build>
70 </project>
```

Code B.5: `TracingOverheadTest.java` – Example program to test the overhead introduced by tracing activity

```java
public class TracingOverheadTest
{
    public static void main(String[] args)
                            throws InterruptedException
    {
        for (int J=0; J<10000; J++) //10K
        {
            Thread t1 = new Thread(new Runnable()
            {
                @Override
                public void run()
                {
                }
            });

            Thread t2 = new Thread(new Runnable()
            {
                @Override
                public void run()
                {
                }
            });

            // Start both threads
            t1.start();
            t2.start();

            // Wait for both threads
            t1.join();
            t2.join();
        }
    }
}
```

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