Università
della
Svizzera
italiana

Faculty
of
Informatics

Instrumentation and Performance Analysis of Distributed Systems with Freud

Stefano Taillefert

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Supervised by
Prof. Antonio Carzaniga

Bachelor Project Report

Abstract

Freud is a software performance analysis tool that derives performance annotations from measurements of running systems. The goal of this project is to extend it to instrument and collect data from a distributed software system. This means augmenting the existing implementation to be able to link the data collected over distributed components using causal relations.

Contents

Chapter 1

Introduction

Freud [1] is a software performance analysis tool that derives performance annotations from measurements of running systems. What does that mean? Given a program executable (compiled with some particular option, but let's leave that for later) this tool can measure a series of metrics, like running time and memory usage, while also monitoring the function calls and their parameters. The idea is to analyze this data to find out which parts of the software are the slowest or most resource-consuming, allowing the developers to fine-tune their code.

The goal of Jung, this project, is to extend the existing tool to collect data from a distributed software system, like a desktop application executing Remote Procedure Calls, or a web server querying a database. This means augmenting the existing implementation to be able to merge the data collected over the various components in a single trace and exporting it in a way that allows other programs to analyze it.

Due to the complexity of the operation, Jung can't (yet?) inject code in a compiled binary but needs to be used as an external library; this can add a considerable overhead on the programmer, but it still produces the desired statistics.

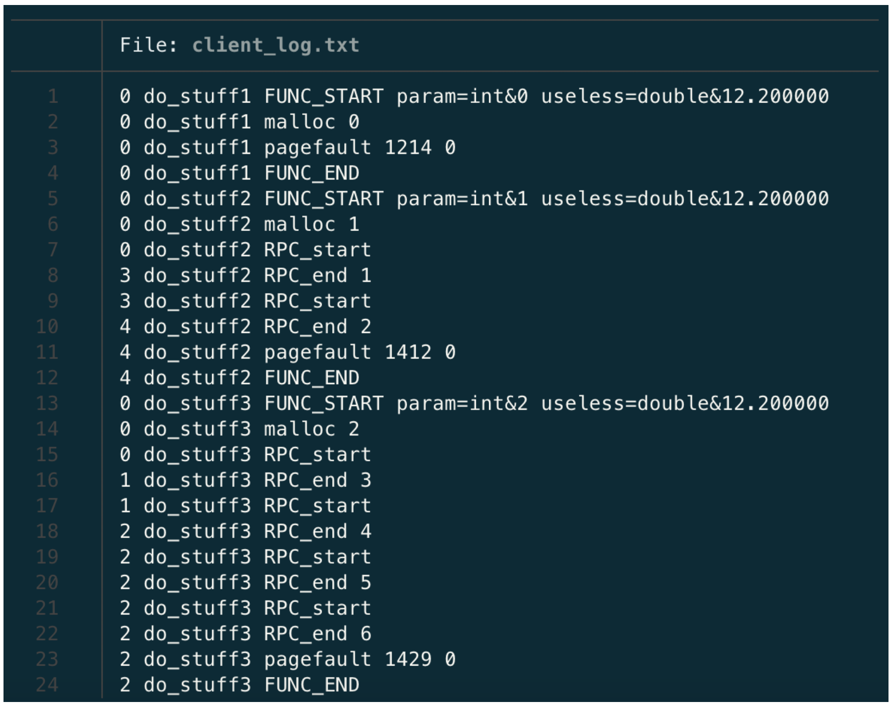
Chapter 2

Performance analysis

As the name implies, performance analysis is a field that deals with the examination of how efficiently some code runs. It's a very vast realm and everyone is - in some way - in need of it; after all, especially in large companies, efficiency is key. Imagine if each Google query took one second less because a developer found out that they could optimize the database query, or if the loading time of a webpage got halved because the webmaster found a function that was holding for no reason: both of those could be the result of a performance analysis study.

As I mentioned, almost every kind of application can be measured, with a vast variety of what we call metrics: execution time, memory or CPU cycles used, lock holding time, and many more. Those can be used in various ways and will be chosen accordingly to the type of application. For example, a single-threaded app will not be concerned about lock holding time, while a frontend web developer isn't necessarily interested in knowing about pagefaults.

There are a lot of existing tools and solutions out there (one of which will be discussed in section 3.1) that can *instrument* the executables: a dedicated tool injects some special code directly in the compiled binary file, following some particular compiler flags. This generated code then measures different parameters, keeping track for example of starting and ending times, memory allocations, and so on. At the end, an information dump is produced to summarize the data, which can then be analyzed in various ways.



```
File: client_log.txt

0 do_stuff1 FUNC_START param=int&0 useless=double&12.200000
0 do_stuff1 malloc 0
0 do_stuff1 pagefault 1214 0
0 do_stuff1 FUNC_END
0 do_stuff2 FUNC_START param=int&1 useless=double&12.200000
0 do_stuff2 malloc 1
0 do_stuff2 RPC_start
3 do_stuff2 RPC_end 1
3 do_stuff2 RPC_start
4 do_stuff2 RPC_end 2
4 do_stuff2 pagefault 1412 0
4 do_stuff2 FUNC_END
0 do_stuff3 FUNC_START param=int&2 useless=double&12.200000
0 do_stuff3 malloc 2
0 do_stuff3 RPC_start
1 do_stuff3 RPC_end 3
1 do_stuff3 RPC_start
2 do_stuff3 RPC_end 4
2 do_stuff3 RPC_start
2 do_stuff3 RPC_end 5
2 do_stuff3 RPC_start
2 do_stuff3 RPC_end 6
2 do_stuff3 pagefault 1429 0
2 do_stuff3 FUNC_END
```

Figure 2.1: An example of performance trace (in this case, produced by Jung)

Chapter 3

Project design

3.1 Freud

My project follows the steps of Freud, a tool developed by Daniele Rogora, an USI PhD student. This software has multiple components; the first two (`freud-dwarf` and `freud-pin`) are tasked with instrumenting the executable via a special tool called PIN [3], developed by Intel. This library - as explained earlier - inserts the instructions necessary to collect the data during the execution. Basically, coding this part means writing code that will write some code to put into other code.

The other part of Freud, which is the one I will be interacting with, is `freud-statistics`. As the name implies, this module (based on the popular `R` library[1]) computes some statistics, such as regression or clustering, given the output of the instrumentation.

3.2 Requirements and analysis

The main idea was to start small and build features incrementally, to ensure that I always had a minimal working prototype. The main objective of Jung - a name chosen after Carl Jung[2], a colleague of Sigmund Freud - is to instrument multiple systems, collect the data and format it. To achieve this, I divided the project in three main components:

- The actual instrumentation library, with an API to track the various metrics
- The merger, which has to collect all the log files from the different systems and merge them in a single coherent trace
- The dumper, which is tasked with creating the binary output that will be passed to `freud-statistics`

The main milestones of the developments were the following: first I had to develop a simple distributed application, based on an RPC library, to be used as an initial test environment. For this part I chose to put together a relatively simple program that sends back and forward some text messages; the server has some delays set up in answering some queries to simulate a long computation.

Following that, I needed to develop an instrumentation for the client side, server side, and – crucially – the RPC library: the idea was to measure some meaningful statistics on all sides involved. The metrics I settled with are:

- Execution time, divided in total, server, and network time
- Memory usage

[1]`https://www.r-project.org/`
[2]`https://en.wikipedia.org/wiki/Carl_Jung`

- Major and minor pagefaults
- Lock holding and waiting time
- Possible memory leaks (experimental)

Except for the first one, all the other ones are divided in client and server side, to allow for an accurate differentiation; futhermore, except for memory leaks, all of them are supported by `freud-statistics`. Possible memory leaks are detected by counting the amount of `malloc` and `free` calls and can therefore be inaccurate in some cases.

Then, i had to devise a method to save and retrieve the measurement logs from all the components. This has been done by dumping the collected information in a text file with some special encoding (see section 4.2 for details) for data types and more complex values.

The next step was to design an algorithm to merge the logs from all the systems into a single coherent trace. This was tricky because I had to correctly identify all the remote calls to allow to trace back which server execution corresponded to which client function. We don't want to debit someone with the computing costs of someone else, therefore I assigned unique IDs to each RPC call to allow to trace back which client function requested which server resource.

Integrating said trace in the existing statistics tool (`freud-statistics`) to derive the performance annotations was the last objective for the coding part. For this I had to rely on the help of its creator, Daniele, to fully understand how to format the data. There were a few hiccups due to some technical issues, but the process concluded perfectly.
Unfortunately, the only abandoned part of the project was to identify some third-party non-trivial distributed applications and analyze them with the created tool. Due to the fact that Jung doesn't work on the binary executable, I needed to access the source code of the application I wanted to analyze. This heavily reduced the spectrum of possible targets, and also considering the little time left we decided to abandon it.

Last but not least, I had to write the report, prepare the poster and the presentation. Due to the current situation, we as a class decided to not hold any presentation this year, therefore this point got reduced to the document you're currently reading.

Have a pizza: this is still on hold but will definitely be completed sooner or later. Every project needs a celebratory pizza at the end.

Chapter 4

Implementation

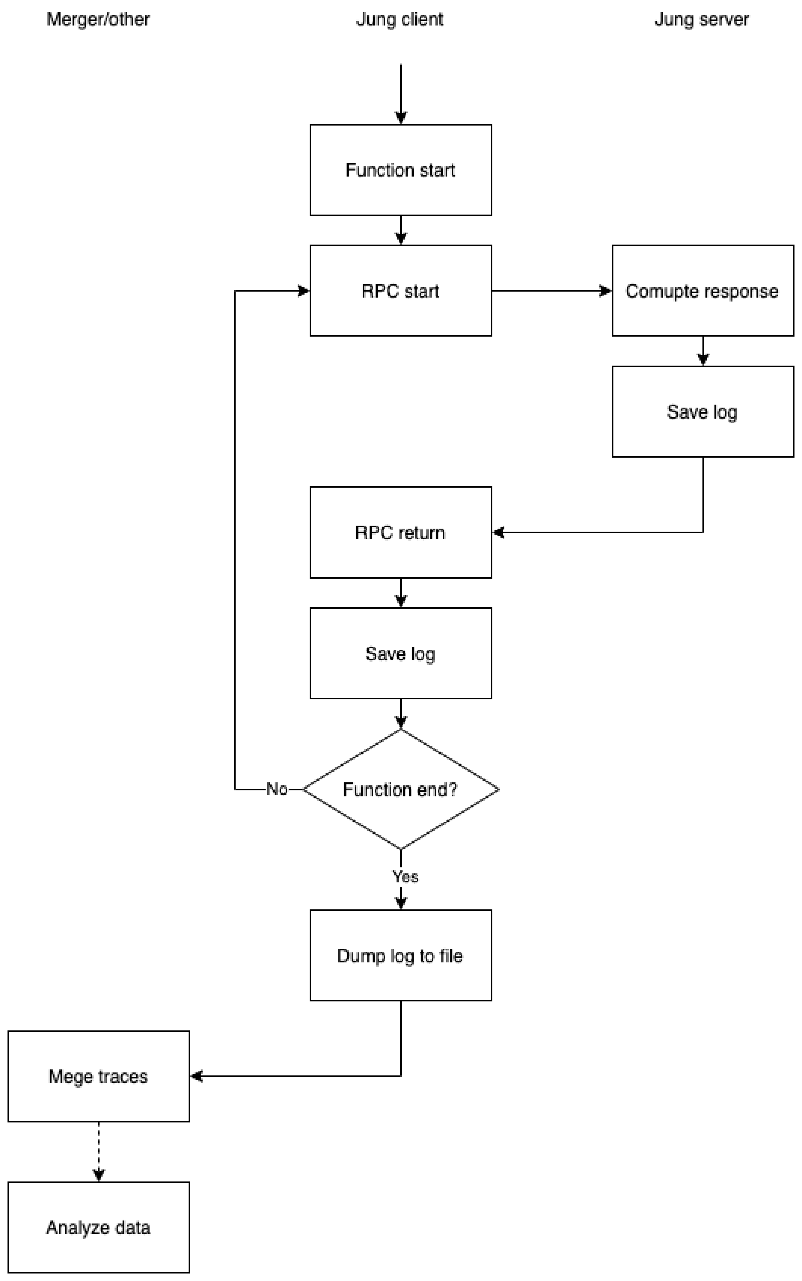


Figure 4.1: Jung's general functioning

4.1 Technologies and tools used

I used gRPC [2] as the RPC library, since it seemed pretty straightforward and simple to use. There are plenty of examples in the documentation and a lot of languages are supported, including C++. On the other hand, Jung is independent from any library: its functions can be used directly from the code, even in a custom RPC implementation.

The choice of language was pretty easy as well: Freud is built entirely in C/C++, so using the same language would increase compatibility. The only choice I had to make was regarding the version: I went with C++17 to benefit from the `filesystem::exists()` function, which I used to check for the existence of previous log files.

To simplify development and testing, I also packaged an auto-building Docker image (`https://hub.docker.com/repository/docker/steeven9/jung`) with the example server in it. This way I could keep the server running on another machine and, for example, test the network times from another remote location.

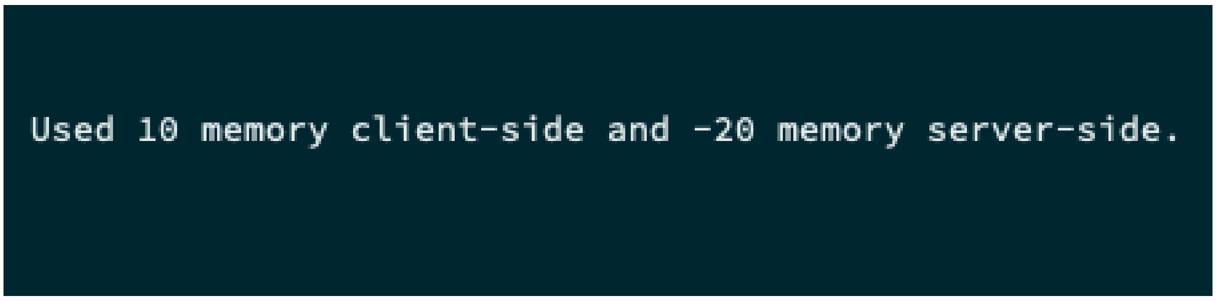
4.2 Issues

The only major problem I had - which I believe to be very common - was that I made some design choices in order to initially simplify my job, but then, with the addition of new features or to fix certain problems, I had to change my approach. The direct consequence was that I had to rewrite some large parts of the code and data structures to adapt to the new requirements.

One instance of the aforementioned problem is that I had to develop some particular encodings to represent the function parameters, since I had to convert from data (the running code) to text (the log file) and vice versa. More specifically, I chose to represent the values as `namet̄ype&value` (e.g. `asdīnt&12` for an integer named `asd` of value 12); this added a supplementary layer of encoding/decoding when saving and reading the data to/from the text files.

When we first started testing the integration with `freud-statistics`, since I was unable to see what was in the binary file, I had troubles checking if I was dumping the metrics correctly, resulting in some weird-looking statistics. With Daniele's help, we managed to make sense of the output and find the offending code parts to patch.

And of course, I had my fair share of miscellaneous issues with pointers, segmentation faults and general weird behaviors. As a positive note, in the process I somehow created a program that frees memory as you run it:



```
Used 10 memory client-side and -20 memory server-side.
```

Figure 4.2: A very peculiar memory usage

Another problem we ran into was that initially we were unable to get `freud-statistics` to find a regression, despite our data was clearly a good candidate for it. Turns out we simply didn't have a good enough p-value, which was easily fixed by getting more samples (details will follow in the next chapter).

Chapter 5

Evaluation

Referring to the task list in section 3.2, I can assert that I successfully implemented all the required features. The results the library provides are accurate (to a certain extent) and repeatable.

To test Jung's functionality I created a demo program that simulates a real use-case of this library: a client program (`jung_client`) sends some requests to a server (you guessed it, `jung_server`) which computes the results and sends them back. To make it more realistic, the server takes roughly the time in seconds equal to the parameter received (with some added randomness), since it simulates a computation. Being a single-threaded sever, this has been achieved by making the server thread sleep for the given input. On the other hand, the client uses a `for` loop to send the requests, so the parameter's value increases gradually; the maximum number of iterations has been set to 30, but it can be changed in the code.

Alas, time and coding constraints limited the amount of testing I could do, meaning that the performance analysis has been tested only with a few scenarios. One of those is illustrated in the plot below:

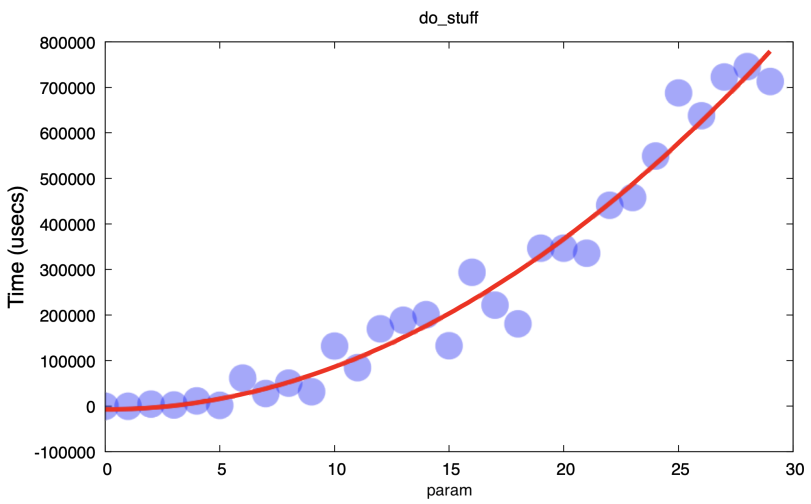


Figure 5.1: The first plot produced by `freud-statistics`

As we can see, our data fits nicely in a quadratic regression, which makes sense if we consider that our program can be represented by the following algorithm:

```
for $i \leftarrow 0$ to $NUM\_MSG$ do
    for $j \leftarrow 0$ to $i$ do
        sleep($j$);
    end
end
```

Another scenario can be represented by making the RPC calls a constant amount of times instead of depending on the parameter, which produces the linear result illustrated below:

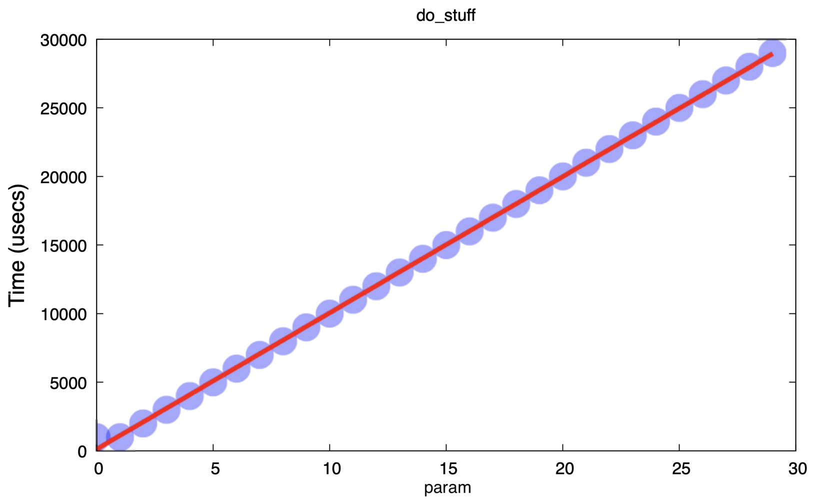


Figure 5.2: The second plot produced by `freud-statistics`

5.1 Testing

Due to the complexity and particular nature of the software, I decided to not implement any automated tests. Opposed to test-driven development, I had a more unstructured way of iterating over the code, since the functionality had to be checked by hand by comparing the produced log files with the program. Therefore, the effective coverage is 0%, but as someone once said:

"Tests don't prove correctness"

5.2 Demo

In this section you can find instruction on how to run a demo program and analyze the obtained data.

To install and compile all the required software, simply run the `install.sh` script from the Jung repository. In case of failure, please refer to the READMEs of each project for more information.

First, start the server:

```
$ ./jung_server
```

While in another shell, run the client:

```
$ ./jung_client
```

Note: if you run the server on another machine, you can pass the `--target=HOSTNAME` argument to the client.

Then, with both the client and server log files in the root folder, merge the traces:

```
$ ./trace_merge
```

This will produce the binary data (under `symbols/`) and a summary of the execution (`trace_log.txt`). We can then run Freud's analysis tool:

```
$ cd ../freud/freud-statistics
```

```
$ ./freud_statistics 3 0 0 do_stuff ../../Jung/symbols/do_stuff/
```

Note: this is an example, refer to Freud's documentation for details and usage.

This should find a nice regression and plot it. That's it!

Chapter 6

Conclusions

I consider the results I obtained pretty satisfying: I managed to realize a working application that complies with the requirements and could be used in the field to measure actual systems (with some limitations, of course). As the evaluation shows, Jung correctly tracks and aggregates metrics, producing an output which can be interpreted by another tool. Different behaviors are correctly picked up and produce different outputs when analyzed, as expected.

From a more personal point of view, the whole project was a great learning experience, both in terms of development and project management; in addition to refreshing my C++ skills, I experienced carrying out a large-ish project on my own, with deadlines and constraints. I would like to add that the way my advisor and I organized the work was very helpful: small steps and weekly meetings allowed to iterate quickly over the code and to keep relatively on track with the schedule. As a matter of fact, the only discarded feature, testing on third-party applications, was not mandatory for the completion of the project.

I'd like to thank Antonio, my advisor, for the opportunity and for guiding me throughout this project; Daniele, Freud's author, for his help understanding his amazing software; my friends Sasha and Brites for their incredible support; and last but not least everyone that supported me during these tiring times. Thank you!

6.1 Future work and possible developments

While this project can be considered a success, there are still a number of improvements that could be implemented. For example a better handling of the data dumping via a separate thread: as of now every function writes the buffered metrics to the log file when it finishes executing. While this is barely noticeable on a small scale, it could add a significative overhead under large loads or in performance-critical systems.

A crucial missing part is an actual instrumentation like Freud's, either through PIN or another similar library, allowing the user to work on the executables instead of having to change the source code.

Other possible improvements would be to support more complex features as parameters, like structs, automatically infer the type of the parameter (opposed as having to manually specify it), and export the data in a more universal format, like csv, to be able to use it in a wider variety of analysis tools.

Bibliography

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[2] gRPC Authors. Documentation | gRPC. https://grpc.io/docs/, 2021. Accessed on 27.04.2021.

[3] Intel Corporation. Pin - A Dynamic Binary Instrumentation Tool. https://software.intel.com/content/www/us/en/develop/articles/pin-a-dynamic-binary-instrumentation-tool.html, 2021. Accessed on 22.05.2021.