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FAKULTA INFORMAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF INTELLIGENT SYSTEMS
ÚSTAV INTELIGENTNÍCH SYSTÉMŮ

PERFORMANCE ANALYSIS OF WEB APPLICATIONS

ANALÝZA VÝKONU WEBOVÝCH APLIKACÍ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis Assignment

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Institut:	Department of Intelligent Systems (DITS)
Student:	**Valent Tomáš**
Programme:	Information Technology
Title:	**Performance Analysis of Web Applications**
Category:	Software analysis and testing
Academic year:	2023/24

Assignment:

1. Get acquainted with the Perun project (performance version system) and the field of software profiling.
2. Study available methods of program instrumentation, resource consumption measurement (e.g., function duration, memory consumption or CPU usage), and existing tools for performance analysis of web applications.
3. Design and implement a tool that measures consumption of at least one resource in web applications, or programming languages used in development of web applications (e.g., JavaScript, TypeScript or ASP.NET). The tool interface should respect the requirements of the Perun project.
4. Design and implement suitable visualisation of the resulting collected data (e.g., flame graph or tree view), or use and enhance at least two of the existing visualisations in Perun.
5. Demonstrate the solution on at least one non-trivial use-case.

Literature:

- Oficiální stránky projektu Perun: https://github.com/Perfexionists/perun
- V8 Profiler: https://v8.dev/docs/profile
- Gregg, B. (2020). Systems Performance, (2nd ed.). Pearson. ISBN: 9780136821694.

Requirements for the semestral defence:
First two points of the assignment.

Detailed formal requirements can be found at https://www.fit.vut.cz/study/theses/

Supervisor:	**Pavela Jiří, Ing.**
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Abstract

The goal of this work is to extend the open-source Performance Version Control System — Perun by implementing a module that is able to profile web pages programmed in TypeScript or JavaScript. The profiler can collect metrics such as website loading time, responsiveness during interactions with the website, or memory consumption. At the same time, the module supports visualization of the measured results using a graph or call graph.

Abstrakt

Cieľ tejto práce je rozšíriť verejne dostupný verzovací systém – Perun implementáciou modulu, ktorý je schopný profilovať webové stránky naprogramované pomocou TypeScriptu prípadne JavaScriptu. Profiler je schopný zbierať metriky ako napríklad dobu načítania webu, odozvu pri interakciách s webom či spotrebu pamäti. Zároveň je modul schopný vizualizovať namerané výsledku pomocou grafu alebo grafom volaní.

Keywords

Typescript, profiling, Perun, continuous monitoring, Node.

Klíčová slova

Typescript, profilovanie, Perun, nepretržié monitorovanie, Node.js

Reference

VALENT, Tomáš. *Performance Analysis of Web Applications*. Brno, 2024. Bachelor's thesis. Brno University of Technology, Faculty of Information Technology. Supervisor Ing. Jiří Pavela,

Performance Analysis of Web Applications

Declaration

I hereby declare that this Bachelor's thesis was prepared as an original work by the author under the supervision of Ing. Jiří Pavela. I have listed all the literary sources, publications, and other sources, which were used during the preparation of this thesis.

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Tomáš Valent
February 2, 2024

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I would like to thank the supervisor of this thesis, Ing. Jiří Pavela, and the technical consultant, Ing. Tomáš Fiedor Ph.D., for their supervision and patience.

Contents

Chapter 1

Introduction

Every programmer wants to create a perfect application. We usually encounter many different problems and bugs that are in our way to do so. One of the most common issues is *performance* of the program.

> Performance is part of the non-functional requirements of software. It can be defined as how efficiently a software can accomplish its tasks. A system is never more performative than its slowest part. And that part is what we call a *bottleneck* or *contention*. If you want to improve the performance of your system, you have to improve the performance of the slowest part. As all your processing is queueing in there, the rest of your system hasn't reached its peak yet. [12]

To optimize such bottlenecks away, one must first detect and locate them. *Profiling* is one of the most common dynamic analysis approaches for gathering performance data about programming. The main goal of profiling is to identify performance issues such as throughput (either operations or data volume per second), IOPS (input/output operations per second), utilization (how busy a resource is, as a percentage), latency (operation time, as an average or percentile) or CPU load. To better understand the gathered data, performance engineers rely on visualizations to help them interpret the overall program performance. Common ways of visualizing the results of profiling (called *profiles*) are heat maps, flame graphs, tree maps, and others.

The main objective of this thesis is to develop a new module that will extend the system for versioning performance profiles *Perun*, developed by the *VeriFIT* group at the Faculty of Information Technology BUT, by a profiler that can profile web applications programmed in *TypeScript*.

TypeScript is a free, strongly typed, compiled, and open-source high-level programming language developed by Microsoft. TypeScript is a syntactic superset of JavaScript which adds static typing. This means that TypeScript adds syntax on top of JavaScript, allowing developers to add types [15]. Unlike JavaScript, TypeScript supports object-oriented programming concepts in the vein of classes, interfaces, and inheritance. [14]

This thesis is organized as follows. Program analysis and profiling are introduced in Chapter 2. Perun, the version control system, is introduced in Chapter 3. A comparison of existing open-source TypeScript profilers is presented in Chapter 4. Analysis of requirements for profiler for this thesis discussed in Chapter 5. The design and architecture of the module are described in Chapter 6. All other information about the implementation is presented in Chapter 7.

Chapter 2

Performance Analysis

This chapter will closely explain profiling as a whole, the types of software analysis, and some profiling concepts.

Performance analysis is a critical aspect of software development and system optimization. Whether you are a developer, a system administrator, or an IT manager, understanding and improving the performance of your applications is necessary. In a time when user expectations are higher than ever, and a fraction of a second can make a significant difference, it is essential to have the knowledge and tools to identify and remove performance bottlenecks.

2.1 Web application profiling

Profiling creates a picture of the project as a whole. They are tools used by developers and performance engineers to identify problematic parts of a program. Problematic parts in the context of profiling mean I/O bottlenecks, CPU bottlenecks, suboptimal database queries, memory issues, power consumption, etc. Profiles are capable of obtaining information about a project such as the number of calls to individual functions, the execution time of functions, memory usage, and allocation, or simply „finding hot paths in your code“. Most profiles can profile a project without directly modifying the project's code. However, there are profiling techniques, especially those based on sampling, where direct code instrumentation is required. [5, 13]

2.2 Static analysis vs. Dynamic analysis

Program analysis can be divided into two groups based on when the analysis is performed — static analysis and dynamic analysis[1].

2.2.1 Static analysis

Static analysis involves analyzing the machine code as well as the source code without actually running the program. It is carried out in the early stages of development to more easily detect program errors. Static analysis is performed, for example, by *compilers* during type checking or analyses for optimization, which identify valid performance-improving transformations. Some tools can also visualize the code in addition to identifying errors.

[1] This section is based on the following sources [9, 1, 4]

Static analysis can easily uncover certain errors that cannot be detected through dynamic analysis. Purely static analysis tools are good because they consider all program paths and are reliable. However, there are many errors, such as memory-related issues, that static analysis may not be able to uncover.

2.2.2 Dynamic analysis

Dynamic analysis does not have a clear definition. Everyone defines it in a different way. One of the definitions by *Michael D. Ernst* states:

> Dynamic analysis operates by executing a program and observing the executions. Testing and profiling are standard dynamic analyses. [1]

Tools performing dynamic analysis must be able to instrument the target code. The analysis code runs as part of the program's normal execution, without disturbing the program's execution. The analysis must maintain some kind of analytical state, which we can call metadata. These are crucial for dynamic code analysis. An example of dynamic analysis could be profiling.

2.2.3 Continuous monitoring

A real-time monitoring method called *continuous monitoring* is used to examine production applications in order to identify and resolve performance issues that impact application user experience. Identifying issues and opportunities for improvement, it entails collecting data on execution-related parameters such as CPU use, disk I/O consumption, and function call time. Continuous profiling provides developers with additional insights into functions that are performed. On the other side, engineers have the ability to gather CPU utilization data and note how to measure consumption for better performance. [6]

Continuous monitoring can be used to profile web pages, in cybersecurity, or in hospitals it can be „vital signs monitor“.

2.3 Sampling

During profiling, sampling collects statistical data about an application's activities and is a useful beginning point for finding places to speed up your program. The sampling method collects information about the functions in your application at predefined intervals. Information about the application is gathered through data collection by sampling the data at a regular period or sampling frequency, such as once every millisecond. To build a model of where time was spent in the application, the gathered data is evaluated. Sampling could be a good option if you require precise call time data or are searching for performance problems in an application for the first time.

Sampling is less accurate in terms of calls, but it is inexpensive for the profiler and has less impact on how the program under profile runs.

2.4 Instrumentation

During a profiling run, instrumentation profiling gathers comprehensive data about the work the tasks done by an application. Tools that either insert code into a binary file to record timing data or use callback hooks to gather and release precise timing and call count data

while a program is operating are used for data collecting. Comparing the instrumentation method to sampling-based techniques reveals a large overhead.

2.5 Sampling vs. Instrumentation

The benefit of sampling is that it requires less overhead and, as a result, is more likely to be statistically the most representative of reality in production. The benefit of instrumentation profiling is that you can obtain precise call counts on how many times your functions were invoked. This provides significantly more comprehensive information than standard sampling, which might distort time in particular cases. Functions that don't perform anything but are called frequently, for example, will seem more than they would in a real-world scenario.

Every function call in your application is annotated and instrumented with instrumentation so that when it is executed, it is included in the trace along with information about the caller. The current call stack is queried from the CPU at regular intervals with sampling, and each frame is added to the trace.

2.6 Tracing

Tracing offers further information about how frequently a method was run. Tracing is useful if you require precise measurements of call numbers. Tracing has a greater influence on the speed of your code during collection, whereas sampling has a minor overhead. Furthermore, tracing might be slower to examine since it takes longer to view the data after it has been collected.

2.7 Profiling metrics

In profiling, we can measure different *metrics*. Metrics show us how effectively the is program written and we can use them to visualize graphs, heat maps, and so on. Those metrics and visualizations can be used to analyze the performance of the program. Now we are going to list the most common performance metrics.

- **Total time** – The total time of a program is the easiest metric to measure while profiling. Profiling time involves measuring the amount of time for a specific piece of code or a program to execute. This can help identify bottlenecks and performance issues in the code.
  - **Wall time** – is time of a specific function. It is a difference between the start and the end of the function.
- **Functions calls** – The number of calls for each function in the program can be helpful in finding non-optimal parts of the code. simple solution can be the cached result of the function so that the developer does not have to call it more than it is needed. For example, if the function is loading data from a database it can save many function calls but also total performance time.
- **CPU** – CPU profiling focuses on monitoring the usage of the central processing unit (CPU). It helps identify how much CPU time is spent on various functions or code sections, aiding in optimizing code for efficiency.

- **Memory** – Memory profiling assesses the usage of system memory (RAM) by a program. It helps find memory leaks, inefficient memory allocation, and excessive memory usage, which can lead to performance problems or crashes.
- **Instructions** – Instruction profiling involves counting the number of machine instructions executed by a program. This can be useful for identifying code segments that may be expensive.

Chapter 3

Perun

In this chapter, we are going to describe what is Perun. **Per**formance **Un**der Control is an open-source lightweight Performance Version System that acts as a wrapper for current Version Control Systems while also managing performance profiles corresponding to different project versions [11]. It also includes a tool suite that allows you to automate performance regression test runs, post-process existing profiles, and understand the findings [10]. [1]

3.1 Overview

Perun has the following advantages over databases and sole Version Control Systems:

1. **Context** – every performance profile has a specific minor version associated with it, which fills in the gaps in your profiles with information about what was changed in the code base, when it was updated, who made the changes, and so on. The profiles themselves provide more details on the application setup or the performance regression run, in addition to the data that was gathered.

2. **Automation** – Perun allows one to easily automate the process of profile collection, eventually reducing the entire process to a single command, and can thus be hooked, for example, when one commits new changes, in the supported version control system to ensure that one never forgets to generate new profiles for each new minor or major version of the project.

3. **Genericity** – The supported format for performance profiles is based on JSON notation, with only minor needs and limits. The Perun tool suite includes a foundational set of general (as well as numerous particular) visualizations, postprocessing, and collecting modules that may be used as building blocks for automating activities and understanding results. Perun has only a few minimal requirements for developing and registering new modules.

4. **Easy to use** – Perun's workflow, interface, and storage are significantly inspired by git systems, with the goal of being easy to use (at least for the majority of prospective users). The current version has a Command Line Interface with git-like commands (e.g., add, status, and log). The Interactive Graphical User Interface is being worked on right now. [10]

Figure 3.1 shows a comparison of the git and Perun systems.

[1] This chapter is based on Perun documentation [10, 2]

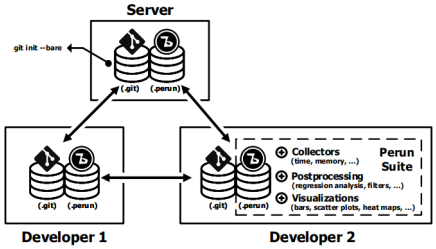

Figure 3.1: Comparison of the git and Perun systems [10]

3.2 Architecture

Perun is a tool package and a wrapper for Version Control Systems (VCS) like git that keeps track of performance profiles for different project versions. Figure 3.2 shows the workflow of the Tracer profiler is divided into four steps. [2]

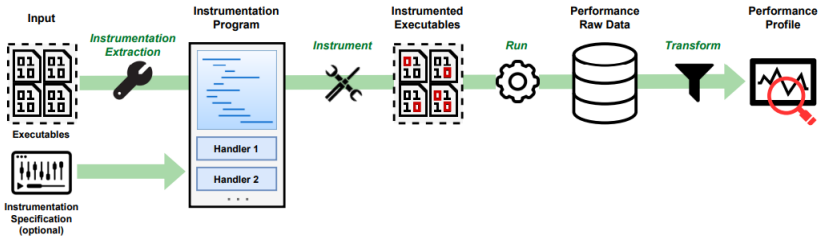

Figure 3.2: Comparison of the git and Perun systems [2]

- The input executables are then utilized to determine possible instrumentation locations (unless the user explicitly specifies them), and an instrumentation program and instrumentation handlers are built. The instrumentation program tells the instrumentation tool how to do the instrumentation, and the handlers tell the instrumentation tool what to do at specific instrumentation points.
- The produced instrumentation software and handlers are used to instrument the input executables.
- The executables received are started (in the manner chosen by the user) and generate raw performance statistics.
- Finally, the raw performance statistics are then turned into a performance profile.

Perun's internal architecture is organized into three sections: logic (commands, jobs, runners, and store), data (vcs and profile), and tool suite (collectors, postprocessors, and visualizers). The foundation of Perun is data, which includes profile manipulation and supporting wrappers (currently git and basic custom vcs) over existing version control systems. The logic is in charge of automation and higher-level logic operations, as well as profile development. Furthermore, the Perun suite includes a collection of collectors for profile creation, a collection of postprocessors for transformation, and a variety of visualization approaches and wrappers for graphical and command-line interfaces. [10]

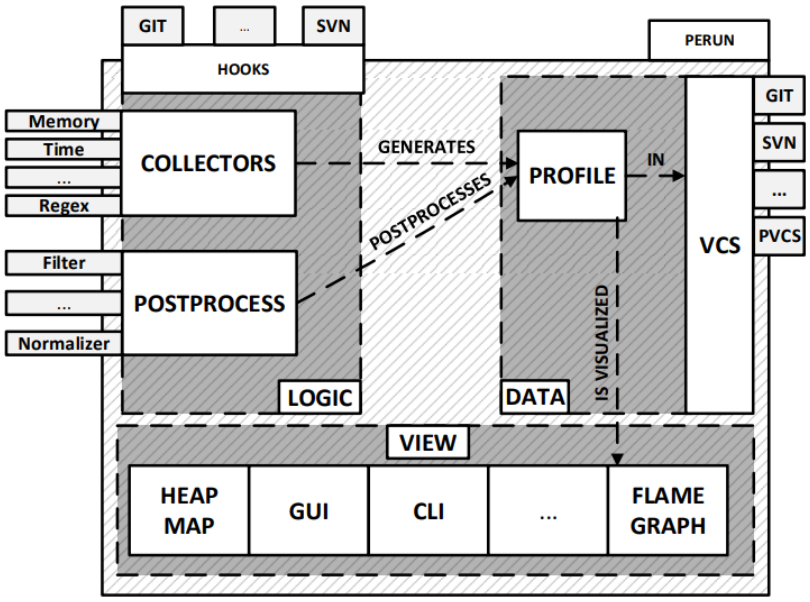

Figure 3.3: The scheme above shows the basic decomposition of Perun suite into sole units [10]

3.3 Detecting Performance Changes

Every change of the project, and every new minor version, can cause a performance degradation of the project. And manual evaluation of whether the degradation has happened is hard. Perun allows one to automatically check the performance degradation between various minor versions within the history and protect the project against potential degradation introduced by new minor versions. Potential changes in performance are then reported for pairs of profiles, together with more precise information, such as the location, the rate, or the confidence of the detected change. The detection of a performance change is always checked between two profiles with the same configuration (i.e. collected by the same collectors, postprocessed using the same postprocessors, and collected for the same combination of command, arguments, and workload). These profiles correspond to some minor version (so-called target) and its parents (so-called baseline). But baseline profiles do not have to be necessarily the direct predecessor (i.e. the old head) of the target minor version and can be found deeper in the version hierarchy. [10]

Chapter 4

Existing TypeScript profilers

In this chapter, we will briefly describe existing profilers that support analyzing the performance of TypeScript applications.

4.1 V8

V8 is an open-source high-performance Javascript and WebAssembly engine made by Google that also supports profiling TypeScript. V8 is also used in other third-party profiling tools such as *Node*, *Chrome*, *Deno*, and so on. V8 is able to collect data about Walltime, CPU and Memory profiling[1].

4.1.1 TS-Node

As the title suggests, TS-node is a TypeScript execution engine for Node.js and REPL (Read-Eval-Print Loop) [3]. Node.js supports profiling of TypeScript applications using *TS-Node* that is based on *V8*. The output of the profiling is *.log* file that needs to be processed afterward to be in human-readable format Figure 4.1 shows an example output of profiling a Node application[2].

```
Statistical profiling result from isolate-0x5872c50-12236-v8.log, (1482 ticks, 0 unaccounted, 0 excluded).

 [Shared libraries]:
   ticks  total  nonlib   name
    1098   74.1%          /home/arcanebuchta/.nvm/versions/node/v14.21.3/bin/node
      96    6.5%          /usr/lib/x86_64-linux-gnu/libc.so.6
       4    0.3%          /usr/lib/x86_64-linux-gnu/libstdc++.so.6.0.32

 [JavaScript]:
   ticks  total  nonlib   name
       4    0.3%    1.4%  LazyCompile: *resolve path.js:1067:10
       2    0.1%    0.7%  LazyCompile: *normalizeString path.js:59:25
       1    0.1%    0.4%  LazyCompile: *realpathSync fs.js:1723:22

 [C++]:
   ticks  total  nonlib   name
     153   10.3%   53.9%  epoll_pwait@@GLIBC_2.6
      47    3.2%   16.5%  __write@@GLIBC_2.2.5
      16    1.1%    5.6%  pthread_cond_signal@@GLIBC_2.3.2
      13    0.9%    4.6%  fwrite@@GLIBC_2.2.5
      13    0.9%    4.6%  __mprotect@@GLIBC_PRIVATE
```

Figure 4.1: Node.js profiling output

[1] You can find out more about V8 here: https://v8.dev/docs
[2] You can find out more about TS-Node here: https://www.npmjs.com/package/ts-node

4.1.2 Chrome built-in profiling

Chrome like other browsers has its built-in profilers. We can find it by opening any browser tab and clicking *F12* or right-click select *Inspect*. After this, we can find it in *Performance* tab . In Figure 4.2 we can see an example output of Chrome.

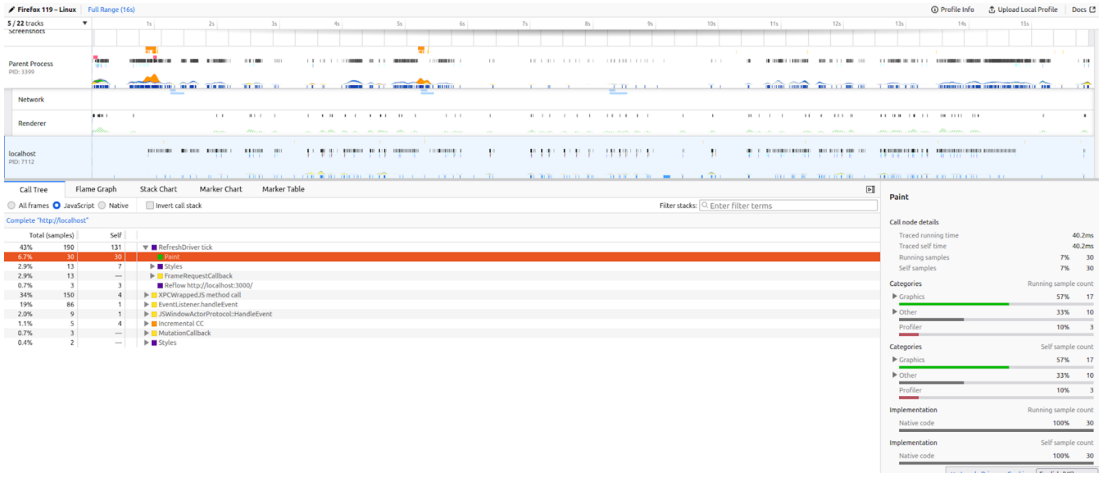

Figure 4.2: Chrome profiling output

4.1.3 Deno

Deno is primarily a TypeScript profiler that runs the server that serves the website. We can think of Deno as the server-side profiler, for example for profiling Node. So it cannot be used to profile client site TypeScript webs.

4.2 JSC

JSC or *JavaScriptCore* is Javascript profiler also supporting typescript. For instance, the *Bun* package management for Node uses it. A sample profiler from JavaScriptCore powers the JavaScript and Events timeline in Web Inspector. JSC's previous tracing profiler has been replaced with the sampling profiler. In addition to being orders of magnitude quicker than the previous tracing profiler, it offers more precise information about where time is spent inside the running application. Instrumentation is inserted into the operating program by tracing profilers. [16]

4.3 Other Profilers supporting TypeScript

In this section, we will shortly introduce other possibilities to profile TypeScript. We aim to emphasize that these profilers can profile *Node.js* and *Typescript*, but it is not their primary focus to do so.

- Gecko profiler — like Chrome, Firefox also has built-in profiling for web applications. It can be used the same way as the one in Chrome as we described here 4.1.2. Gecko Profiler is basically a C++ component that is used for instrumenting Gecko. It is fully configurable and supports a wide range of data sources and recording modes. It

is primarily used as a statistical profiler, pausing the execution of threads registered with the profile in order to collect a sample. [8]. In Figure 4.3 we can see how does the output can look like.

- OProfile — does not profile during runtime of the web. OProfile is part of Linux command *operf*[3]
- Intel VTune — is primarily designed for profiling native code, including C, C++, and Fortran. While it can profile Node.js applications to some extent, its focus is not on TypeScript or JavaScript. In Figure 4.4 we can see how does the output can look like.

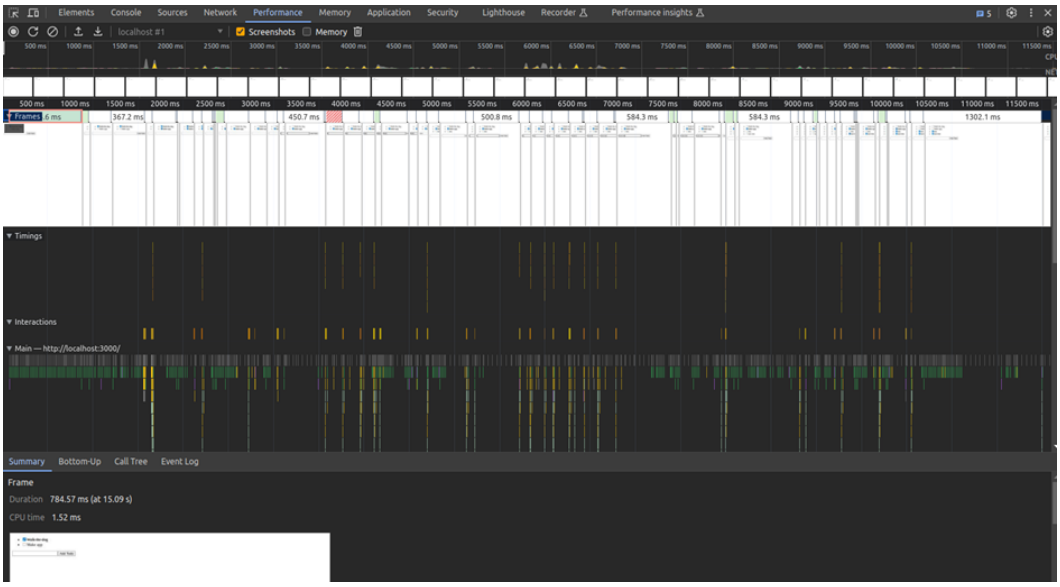

Figure 4.3: Firefox profiling output

[3]See more about *operf* here: https://man7.org/linux/man-pages/man1/operf.1.html

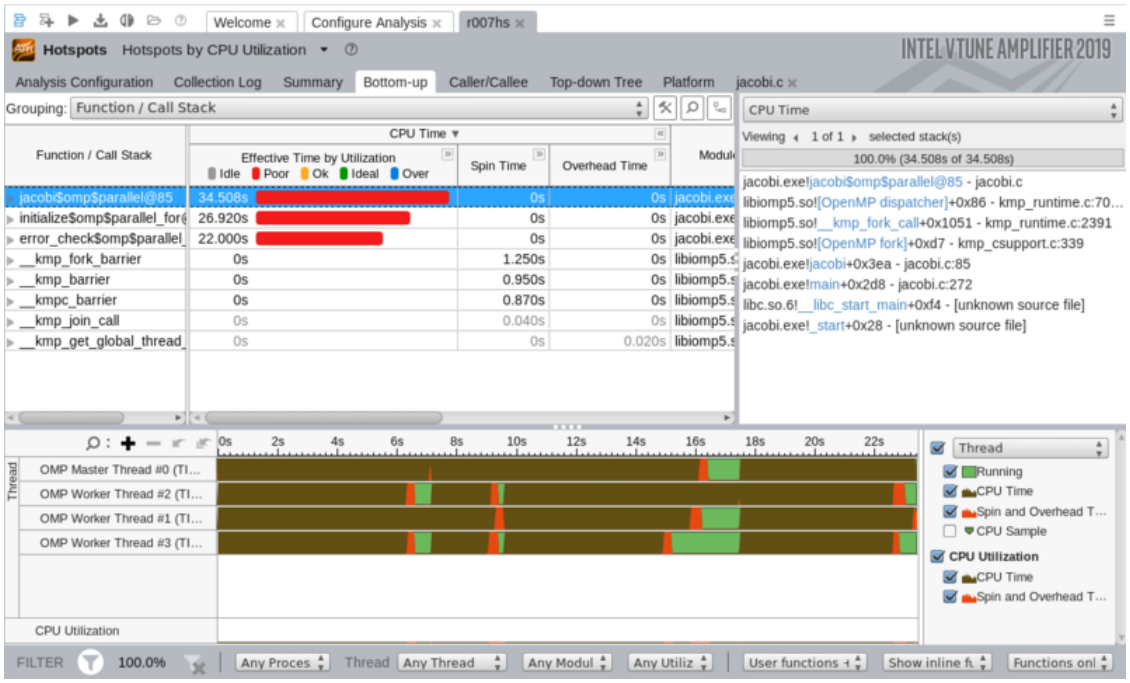

Figure 4.4: Intel VTune profiling output [7]

4.4 Summary

In this section, we will show you the section summary for all profilers mentioned above.

	Sampling + Tracing	Instrumentation	License
V8	Yes	Yes	Open-source
JSC	Yes	No	Open-source
Gecko profiler	Yes	Yes	Open-source
OProfile	Yes	No	Open-source
VTune	Yes	Yes	Proprietary

Table 4.1: Profilers summary

Chapter 5

Analysis of requirements

In this chapter, we are going to summarize the intended functionality of the TypeScript profiler and list basic requirements.

5.1 Analysis of requirements for TypeScript profiler

This section describes the intended requirements for the TypeScript profiler. Our focus centers on three core elements:

Metrics – Firstly, the most crucial metric to measure is the time taken for the initial pixels of the website to load and appear on the screen during the first loading of the website. Secondly, *latency* while interacting with the website, and last but not least measuring the memory consumption to gauge the overall resource utilization.

Overhead in general is expected to be as minimal as possible, but since this is only the first version of the profiler it is not the case. The required overhead for now is maximally 50%.

Visualizations – metrics collected by the profiler need to be visualized. For this purpose, the module will use *D3JS* to make a graph and also an option to make a call graph using an open-source library for TypeScript[1].

[1] If the profiler will be written in TypeScript, see more here: https://github.com/whyboris/TypeScript-Call-Graph

Chapter 6

Architecture for Profiling

Chapter 7

About implementation

Chapter 8

Conclusion

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