

# A New Program Autotuning Methodology Using Cloud Computing and OpenTuner

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**Abstract.** The OpenTuner framework provides domain-agnostic tools for the implementation of autotuners. It sequentially evaluates program configurations exploring search spaces that are commonly very large. This paper proposes a new methodology and a protocol for the distributed execution of autotuners. Both contributions are implemented in the OpenTuner framework as an extension to the OpenTuner measurement driver by distributing and parallelizing the measurement process via cloud computing resources. The performance evaluation shows that autotuners implemented with the extension are able to achieve good performance using few and cheap cloud computing resources, lowering the cost and the power consumption of producing an autotuned solution.

Pedro: A very short summary of the results will be provided in the abstract, as well as a brief discussion of the result normalization research question.

## 1. Introduction

The program autotuning problem fits in the framework of the Algorithm Selection Problem, introduced by Rice in 1976 [1]. The objective of an autotuner is to select the best algorithm, or algorithm configuration, for each instance of a problem. Algorithms or configurations are selected according to performance metrics such as the time to solve the problem instance, the accuracy of the solution and the energy consumed. The set of all possible algorithms and configurations that solve a problem defines a *search space*. Various optimization techniques search this space, guided by the performance metrics, for the algorithm or configuration that best solve the problem.

There are specialized autotuners for domains such as matrix multiplication [2], dense or sparse [4] matrix linear algebra, and parallel programming [5]. Other autotuning frameworks provide more general tools for the representation and search of program configurations, enabling the implementation of autotuners for different problem domains [6, 7].

The OpenTuner framework [6] provides tools for the implementation of autotuners for various problem domains. It implements different search techniques that explore the same search space for program optimizations. Although support for parallel compilation is provided in the framework the empirical exploration of the search space, that is, running and measuring program execution time, is done sequentially.

The contributions of this paper are a new methodology and a protocol for the distributed execution of autotuners using cloud computing resources. The methodology

[Pedro, na próxima versão remova essas notas laranjas. Se vc ainda precisar lembrar de algum conteúdo dessa notas, ponha como comentário direto no .tex. Isso é necessário para que a gente já consiga ter a versão o mais perto possível da final, principalmente com relação às páginas ocupadas]

The -> There

framework -> framework,

[adicionar vírgula]

and protocol are implemented as extensions to the OpenTuner framework distributing and parallelizing the exploration of optimization spaces by combining results obtained from virtual machines ~~running in a network~~. A local machine (LM) runs the main OpenTuner application and several virtual machines (VM) run measurement modules that provide results when requested, performing more efficient exploration of the search space.

The interactions between the local and virtual machines follows the client-server model. The local machine runs a measurement client that requests results from various measurement servers running in virtual machines hosted at the Google Compute Engine (GCE). We compare the performance of our extension with the unmodified framework in a benchmark of applications, identifying the problem domains that benefit from this cloud-based approach.

The rest of the paper is organized as follows. Section 2 discusses related work. Section 3 discusses the architecture of the OpenTuner framework. Section 4 presents the proposed methodology, the architecture of the measurement driver extension, the GCE interface and the application protocol. Section 5 discusses the result normalization strategies. Section 6 describes the experiments performed and the applications used in the benchmark. Section 7 discusses the results obtained. Section 8 concludes the paper.

## 2. Related Work

Rice's conceptual framework [1] formed the foundation of autotuners in various problem domains. In 1997, the PHiPAC system [2] used code generators and search scripts to automatically generate high performance code for matrix multiplication. Since then, systems tackled different domains with a diversity of strategies. Whaley *et al.* [3] introduced the ATLAS project, that optimizes dense matrix multiply routines. The OSKI [4] library provides automatically tuned kernels for sparse matrices. The FFTW [8] library provides tuned C subroutines for computing the Discrete Fourier Transform. In an effort to provide a common representation of multiple parallel programming models, the INSIEME compiler project [5] implements abstractions for OpenMP, MPI and OpenCL, and generates optimized parallel code for heterogeneous multi-core architectures.

Some autotuning systems provide generic tools that enable the implementation of autotuners in various domains. PetaBricks [9] is a language, compiler and autotuner that introduces abstractions, such as the `either...or` construct, that enable programmers to define multiple algorithms for the same problem. The ParamILS framework [7] applies stochastic local search methods for algorithm configuration and parameter tuning. The OpenTuner framework [6] provides ensembles of techniques that search spaces of program configurations. Bosboom *et al.* and Eliahu use OpenTuner to implement a domain specific language for data-flow programming [10] and a framework for recursive parallel algorithm optimization [11].

In a progression of papers [12, 13, 14], Gupta *et al.* provide experimental evaluations of the application of cloud computing to high performance computing, describing which kind of applications has the greatest potential to benefit from cloud computing. Their work highlights small and medium scale projects as the main beneficiaries of cloud computing resources.

Pedro: Provide a better discussion of Gupta *et al.*'s results.

more efficient exploration of the search space. -> [more efficient than what? You need to finish properly the sentence]

at the Google Compute Engine (GCE)  
-> at the cloud (in this work, the Google Compute Engine — GCE — was used)

discusses -> presents

[Na verdade não acho que vc precisa falar mais dos resultados do Gupta, mas sim emendar no fim do parágrafo uma justificativa, a partir do trabalho dele, para dizer porque vc está fazendo esse seu trabalho de tentar rodar os autotuners na nuvem. O trabalho dele então conclui que autotuners são exemplos de aplicações que se beneficiariam da nuvem? Se não, então é melhor vc remover esse parágrafo e essas referências. Se sim, vc tem que escrever isso]

Pedro: Justify the choice of OpenTuner as the modified system, by saying it is a domain-agnostic tool that has, to the best of our knowledge, no equivalent in scope

[O principal problema da seção ao meu ver nem é isso mas sim a ausência de comparação dos trabalhos relacionados com o seu. O que o seu faz que os outros não fazem? O ideal é que no fim de cada parágrafo desta seção vc termine o parágrafo com frases fazendo essa comparação]

code -> code of OpenTuner

### 3. OpenTuner

OpenTuner search spaces are defined by *Configurations*, that are composed of *Parameters* of various types. Each type has restricted bounds and manipulation functions that enable the exploration of the search space. OpenTuner implements ensembles of optimization techniques that perform well in different problem domains. The framework uses *meta-techniques* to coordinate the distribution of resources between techniques. Results found during search are shared through a database. An OpenTuner application can implement its own search techniques and meta-techniques, making the ensemble more robust. The source code is available<sup>1</sup> under the MIT License.

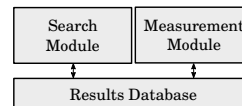


Figure 1. Simplified OpenTuner Architecture.

Figure 1 shows a high-level view of OpenTuner's architecture. Measurement and searching are done in separate modules, whose main classes are called *drivers*. The search driver requests measurements by registering configurations to the database. The measurement driver reads those configurations and writes back the desired results. Using the measurement driver available in the framework, the measurements are performed sequentially.

Before running the user-defined measurement function the OpenTuner measurement driver calls compilation hooks that can be run in parallel using Python threads. When the autotuned program needs to be compiled only once, as in the Travelling Salesperson example shown in Section 6, the autotuner could respond to more simultaneous result requests if the measurement driver was able to also parallelize the runs of the user-defined measurement function.

OpenTuner implements optimization techniques such as the Nelder-Mead [15] simplex method and Simulated Annealing [16]. A resource sharing mechanism, called *meta-technique*, aims to take advantage of the strengths of each technique by balancing the exploitation of a technique that has produced good results in the past and the exploration of unused and possibly better ones.

#### Implementation Details

The implementation follows the client-server model, distributing measurements of program configurations between a group of virtual machines running *MeasurementServers* in GCE. The server waits for measurement requests from a client, and maintain copies of the program to be tuned and the user-defined function that measures configurations.

Hosted at GitHub: [github.com/jansel/opentuner](https://github.com/jansel/opentuner)

function -> function,

[Faltou a vírgula]

was -> is

Implementation Details -> The Proposed Methodology and Protocol

[Não use esse título "Detalhes de implementação". Fica parecendo que o artigo só fala de uma implementação, o que diminui em muito a contribuição científica]

implementation -> methodology and the proposed protocol

GCE -> cloud

waits -> wait

Hosted at GitHub: [github.com/jansel/opentuner](https://github.com/jansel/opentuner) -> <http://github.com/jansel/opentuner> . Accessed at December 22, 2015.

encapsulate -> encapsulates

Figure 4 -> [Não faz sentido a figura 4 aparecer depois da figura 2 e 3 sendo que ela foi citada antes. Mova ela para esta página e transforme ela na figura 2]

of the implementation. -> needed in our proposal.

GCE -> cloud

interface -> interface (in our implementation, the CGE interface)

them -> then

An interface ~~was also implemented~~ to encapsulate the communication from the client enabling a considerably lower implementation effort for the client. Figure 4 shows a rough estimate of the implementation effort for the three components of the implementation.

The machine running the OpenTuner autotuner runs a *MeasurementClient*, an extension of the native *MeasurementDriver*, that instead of compiling and running result requests locally, uses the GCE interface to route requests to virtual machines and then saves the results to the results database.

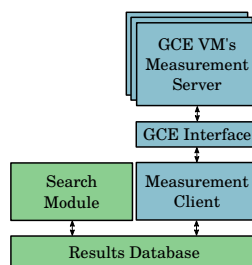


Figure 2. A high-level view of the architecture.

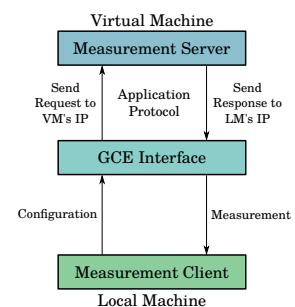


Figure 3. A lower-level view of the architecture.

8 and 9 -> 2 and 3

extension -> extension to the OpenTuner we are proposing

8 -> 2

Figure 2 and 9 present an overview of the architecture of the extension. Figure 3 presents the architecture of an OpenTuner application running the measurement client and communicating with the measurement servers. Green boxes in the figure represent OpenTuner modules that will not be modified, and blue boxes represent new or modified modules.

Figure 3 shows, on a lower level of abstraction, the interactions between the measurement client and servers. The client requests results from the server through a wrapper of the GCE Python API. The GCE interface also encapsulates the application protocol used in the client-server communication.

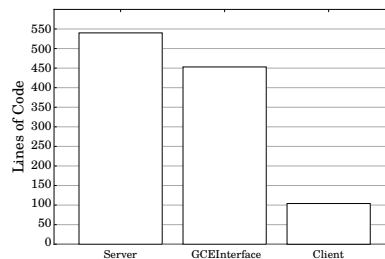
The remaining of this section describes the extension implementation in further detail, the GCE interface and the application protocol.

#### 4.1. Measurement Server and Client

OpenTuner controls the execution flow of an application with the *main* function of the *RunningRunMain* class. This function initialises the database and the search and measurement modules. It then calls the *main* function of the search driver, which runs the main loop of the application. The search driver generates configurations to be tested and saves them to the database. It then calls the *process\_all* function of the measurement driver and blocks until the function returns.

The *process\_all* function calls the *run\_desired\_results* function, which is able to run compilations in parallel but only sequential measurements. The modified *MeasurementDriver* initialises the GCE interface during its own initialisation. During

[Onde está o algoritmo disso? Não é fácil entender assim. Mostre o algoritmo e no texto vc explica o algoritmo. Fica muito mais fácil e faz mais sentido prum artigo de um evento de computação]



**Figure 4. An estimate of the implementation effort, measured in lines of code.**

execution the overridden `process_all` and `run_desired_results` functions route the result requests to the virtual machines using the *GCEInterface*.

An instance of the *MeasurementServer* runs in every virtual machine. The server is installed after the machine's initialisation and waits for TCP connections from a single client. ~~The application protocol used in communications between the clients and servers is described in Section 4.3.~~

#### 4.2. GCE Interface

The interactions between the local *MeasurementClient* and the virtual machines' *MeasurementServers* are mediated by the *GCEInterface*, a wrapper of the GCE Python API. The interface starts and configures virtual machines storing each measurement server's IP.

The interface enables the *MeasurementClient* to request results from the servers without knowledge of the application protocol. Running our client-server implementation in another cloud environment would require a new interface that manages virtual machines in this environment, but no modifications are needed to the server or client.

#### 4.3. Application Protocol

This section describes the text-based application protocol used in the client-server communications mediated by the *GCEInterface*. Note the `CLONE` message. The user's OpenTuner application must be a git project available via `HTTP`. The application will be cloned to the virtual machine by the server and used to obtain the autotuning results requested by the client.

**Messages** Table 1 shows all the messages in the protocol, a brief description of their meaning and their string format. The client must send a `MEASURE` message for each configuration that is measured. The server returns a unique ID that is used to retrieve the results when they are ready. This is done by sending a `GET` message.

**Server Responses** The server responds to each request with a message template and trailing, message-specific parameters. Responses always start with the correspondent command name and end with a newline character. Each response contains the current

implementation -> mechanism

[Tem que revisar a nomenclatura das coisas. Hora chama de implementação, hora de metodologia, hora de protocolo. Em particular, não gosto de ficar chamando de implementação. Isso reduz a contribuição. É necessário mostrar algoritmos!]

Command	Function	Message
START	Sets the server's status to AVAILABLE	'START'
STOP	Sets the server's status to STOPPED	'STOP'
STATUS	Requests the server current status	'STATUS'
DISCONNECT	Disconnects from the server	'DISCONNECT'
SHUTDOWN	Disconnects and shuts the server down	'SHUTDOWN'
CLONE	Clones a git repository to the virtual machine	'CLONE REPO_URL DIST_DIR'
LOAD	Imports the user's MeasurementInterface into the server	'LOAD TUNER_PATH INTERFACE_NAME'
MEASURE	Computes the measurement for a given configuration	'MEASURE CONFIG INPUT LIMIT'
GET	Requests a configuration's result	'GET RESULT_ID'

**Table 1. Server messages.**

server status (SERVER\_STATUS) and error code of the command (ERROR\_STATUS). The optional argument list ([ARGS...]) contains the measurement result, for example, in the case of a successful GET response. Figure 5 shows the format of a server response.

```
'COMMAND ERROR_STATUS SERVER_STATUS [ARGS...] [MESSAGE]'
```

**Figure 5. The format of a server response.**

**Code Availability** The code for the measurement server, client and the interface is available under the GNU General Public License. -> All the code implemented to the proposed methodology and protocol is publicly available at <http://github.com/phrb/measurement-server>, [http://github.com/phrb/gce\\_interface](http://github.com/phrb/gce_interface) and [http://github.com/phrb/measurement\\_client](http://github.com/phrb/measurement_client) under the GNU General Public License.

[Note que o texto tem que ser um parágrafo normal, sem aquele início em negrito e que a nota de rodapé deve ser removida]

resources -> resources when solving autotuning problems,

**Code Availability** The code for the measurement server, client and the interface is available<sup>2</sup> under the GNU General Public License.

## 5. Result Normalization

The virtual machine instances available in public cloud computing services vary in multiple aspects, such as available memory, number of processing cores and disk size. When autotuning a program for a certain target machine, using instances hosted at a public cloud, it is typical that the target architecture will differ from the virtual machines'. Depending on the configuration of the cloud application the instances could also have different architectures.

To effectively leverage cloud computing resources a normalization technique must be devised that enables the results found in different virtual machines to be valid for the target machine. We present four approaches to this problem. The best approach for each

<sup>2</sup>All code is hosted at GitHub:

[github.com/phrb/measurement-server](http://github.com/phrb/measurement-server)  
[github.com/phrb/gce\\_interface](http://github.com/phrb/gce_interface)  
[github.com/phrb/measurement\\_client](http://github.com/phrb/measurement_client)

problem domain must be experimentally determined, and could be a combination of the approaches described here.

**Autotune Performance Models** Another autotuner could be implemented to optimize parameters of a simple performance model, that would associate a configuration's measurement and the virtual machine that produced it with a conversion function that transposes performance results to the target architecture.

**Ensembles of Virtual Machines** The cloud application could be composed of virtual machines with different architectures. The final performance measurement for a configuration would be built from some combination of the results obtained in these different virtual machines.

**Architecture Simulators** The target machine could be modeled by an architecture simulator such as *zsim* [17], a simulator for multi-core architectures ~~available<sup>3</sup> under the GNU General Public License~~. Using a simulator would solve the normalization problem but introduce other problems, such as the simulator's accuracy and performance.

**Autotune in the Cloud** Finally, the normalization problem could be sidestepped, at least in initial stages of research, by running the servers and clients in the cloud using the same kind of virtual machine.

## 6. Experiments

This section describes the problems that compose the benchmark and the Google Compute Engine's virtual machines and project settings. The performances of the autotuners for each problem in the benchmark were measured in 12 different experimental settings. Each tuning run lasted 15 minutes, used 2, 4 or 8 virtual machines, and was repeated 4 times. We also varied the number of result requests that each virtual machine in a tuning run processed, namely 1, 4, 8 or 16 requests per machine.

### 6.1. Using the Google Compute Engine

All virtual machines used in the experiments had a single vCPU and 3 Gb of RAM (Google Compute Engine machine type `n1-standard-1`). All experiments were performed with machines from the `us-central1-f` zone. We built a virtual machine image with the latest stable Debian distribution and all dependencies installed, speeding up the virtual machines' initialization time.

### 6.2. Travelling Salesperson Problem

The instances of the Travelling Salesperson Problem (TSP) used in the experiments in this paper were obtained from TSPLIB [18]. A TSP solver was implemented as an OpenTuner application. The search space was defined by all the possible permutations, or tours, of cities where the first and last cities are the same. We used two instances, of size 532 and 85900.

<sup>3</sup>Hosted at GitHub: <https://github.com/s5z/zsim>

settings -> settings used to evaluate the efficacy of the proposed methodology and protocol

Gb -> GB

[Vai ter outra seção com outro problema, certo?]

[Amanhã o conteúdo desta seção já tem que estar pronto!]

## 7. Results

Pedro: This section will present and discuss the results, connecting the findings with normalization techniques and problem domains.

### 7.1. Travelling Salesperson Problem

Pedro: Here we will discuss the results for the TSP. We will argue that we achieved results very close to a high-end machine using cheap and low-end virtual machines.

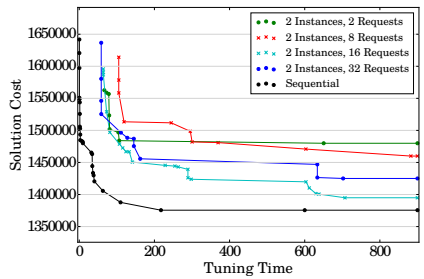


Figure 6. Measurements using two virtual machine instances, solving a TSP instance of size 532.

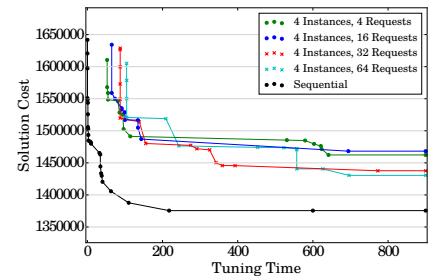


Figure 7. Measurements using four virtual machine instances, solving a TSP instance of size 532.

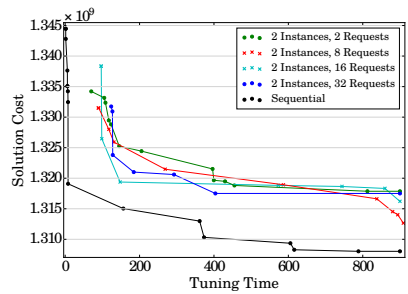


Figure 8. Measurements using two virtual machine instances, solving an instance of size 85900.

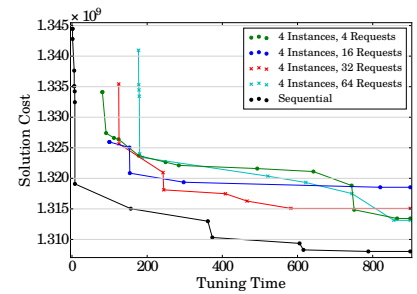


Figure 9. Measurements using four virtual machine instances, solving an instance of size 85900.

[Tem que melhorar. Está muito desconectada com o que está no início do texto. Tem que falar que está propondo uma metodologia, um protocolo e que ambos foram implementados e que a implementação também é uma contribuição. Vc escreve parecendo que só foi uma extensão ao OpenTuner (da forma como está escrito parece ser uma coisa sem contribuição alguma — uma extensão a uma coisa maior). Precisa melhorar isso pra amanhã]

## Conclusion

This paper presented an extension of the OpenTuner autotuning framework enabling it to leverage the cloud computing resources from GCE. We propose four approaches to solve the result normalization problem which would enable transposing the results obtained in virtual machines to a local machine.



[Tem que melhorar as referências. A [1] por exemplo é o que? Um livro? Se sim, qual a editora? Um artigo? Se sim, qual o nome da revista ou congresso e os números das páginas? Tem que revisar tudo.]

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