quiho: Automated Performance Regression Using Fine Granularity Resource Utilization Profiles

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ABSTRACT

We introduce *quiho*, a framework used in automated performance regression tests. *quiho* discovers hardware and system software resource utilization patterns that influence the performance of an application. It achieves this by applying sensitivity analyisis, in particular statistical regression analysis (SRA), using application-independent performance feature vectors to characterize the performance of machines. The result of the SRA, in particular feature importance, is used as a proxy to identify hardware and low-level system software behavior. The relative importance of these features serve as a performance profile of an application, which is used to automatically validate its performance behavior across revisions. We demonstrate that *quiho* can successfully identify performance regressions by showing its effectiveness in profiling application performance for synthetically induced regressions as well as several found in real-world applications.

1 INTRODUCTION

Quality assurance (QA) is an essential activity in the software engineering process [1–3]. Part of the QA pipeline involves the execution of performance regression tests, where the performance of the application is measured and contrasted against past versions [4–6]. Examples of metrics used in regression testing are throughput, latency, or resource utilization over time. These metrics are compared and when significant differences are found, this constitutes a regression.

One of the main challenges in performance regression testing is defining the criteria to decide whether a change in an application's performance behavior is significant, that is, whether a regression has occurred [7]. Simply comparing values (e.g. runtime) is not enough, even if this is done in statistical terms (e.g. mean runtime within a pre-defined variability range). Traditionally, this investigation is done by an analyst in charge of looking at changes, possibly investigating deeply into the issue and finally determining whether a regression exists.

When investigating a candidate of a regression, one important task is to find bottlenecks [8]. Understanding the effects in performance that distinct hardware and low-level system software[1] components have on applications is an essential part of performance engineering [9–11]. One common approach is to monitor an application's performance in order to understand which parts of the system an application is hammering on [5]. Automated solutions have been proposed [7,12–14]. The general approach of these is to analyze logs and/or metrics obtained as part of the execution of an application in order to automatically determine whether a regression has occurred. Most of them do this by creating prediction models that are checked against runtime metrics. As with any prediction model, there is the risk of false/positive negatives.

In this work, we present *quiho* an approach aimed at complementing automated performance regression testing by using system resource utilization profiles associated to an application. A resource utilization profile is obtained using Statistical Regression Analysis[2] (SRA) where application-independent performance feature vectors are used to characterize the performance of machines. The performance of an application is then analyzed applying SRA to build a model for predicting its performance, using the performance vectors as the independent variables and the application performance metric as the dependant variable. The results of the SRA for an application, in particular feature importance, is used as a proxy to characterize hardware and low-level system utilization behavior. The relative importance of these features serve as a performance profile of an application, which is used to automatically validate its performance behavior across multiple revisions of its code base.

In this article, we demonstrate that *quiho* can successfully identify performance regressions. We show (Section 4) that *quiho* (1) obtains resource utilization profiles for application that reflect what their codes do and (2) effectively uses these profiles to identify induced regressions as well as other regressions found in real-world applications. The contributions of our work are:

- Insight: feature importance in SRA models (trained using these performance vectors) gives us a resource utilization profile of an application without having to look at the code.
- Methodology for evaluating automated performance regression. We introduce a set of synthetic benchmarks aimed at evaluating automated regression testing without the need of real bug repositories. These benchmarks take as input parameters that determine their performance behavior, thus simulating different "versions" of an application.

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[1] Throughout this paper, we use "system" to refer to hardware, firmware and the operating system (OS).
[2] We use the term *Statistical Regression Analysis* (SRA) to differentiate between regression testing in software engineering and regression analysis in statistics.

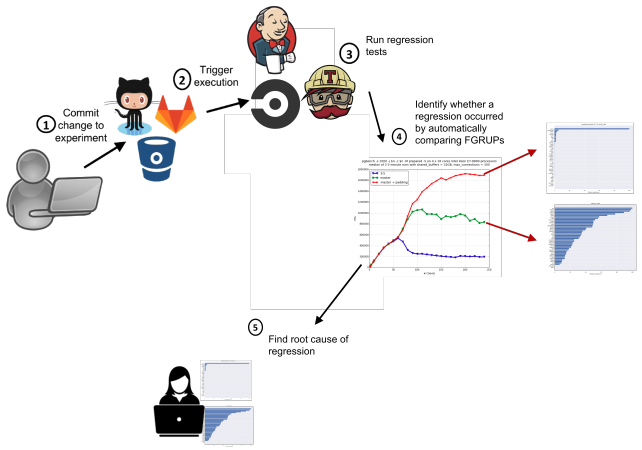

Figure 1: Automated regression testing pipeline integrating fine granularity resource utilization profiles (FGRUP). FGRUPs are obtained by *quiho* and can be used both, for identifying regressions, and to aid in the quest for finding the root cause of a regression.

- A negative result: ineffectiveness of resource utilization profiles for predicting performance using ensemble learning.

Next section (Section 2) shows the intuition behind *quiho* and how can be used to automate regression tests (Section 2). We then do a more in-depth description of *quiho* (Section 3), followed by our evaluation of this approach (Section 4). We briefly show how *quiho*'s resource utilization profiles can not be used to predict performance using some common machine learning techniques (Section 4.4). Section 5 reviews related work and we subsequently close with a brief discussion on challenges and opportunities enabled by *quiho* (Section 6).

2 MOTIVATION AND INTUITION BEHIND *QUIHO*

Fig. 1 shows the workflow of an automated regression testing pipeline and shows how *quiho* fits in this picture.

A regression is usually the result of observing a significant change in a performance metric of interest (e.g. runtime). At this point, an analyst will investigate further in order to find the root cause of the problem. One of these activities involves profiling an application to see what's the patter in terms of resource utilization. Traditionally, coarse-grained profiling (i.e. CPU-, memory- or IO-bound) can be obtained by monitoring an application's resource utilization over time. Fine granularity behavior allows application developers and performance engineers to quickly understand what they need to focus on while refactoring an application.

Obtaining fine granularity performance utilization behavior, for example, system subcomponents such as the OS memory mapping submodule or the CPU's cryptographic unit is usually time-consuming or requires implicates the use of more computing resources. This usually involves eyeballing source code, static code analysis, or analyzing hardware/OS performance counters.

An alternative is to infer fine granularity resource utilization behavior by comparing the performance of an application on platforms with different system performance characteristics. For example, if we know that machine A has higher memory bandwidth than machine B, and an application is memory-bound, then this application will perform better on machine A. There are several challenges with this approach:

1. We need to ensure that the software stack is the same on all machines where the application runs.
2. The amount of effort required to run applications on a multitude of platforms is not negligible.
3. It is difficult to obtain the performance characteristics of a machine by just looking at the hardware spec, so other more practical alternative is required..
4. Even if we could solve 3 and infer performance characteristics by just looking at the hardware specification of a machine, there is still the issue of not being able to correlate baseline performance with application behavior, since between two platforms is rarely the case where the change of performance is observed in only one subcomponent of the system (e.g. a newer machine doesn't have just faster memory sticks, but also better CPU, chipset, etc.).

The advent of cloud computing allows us to solve 1) using solutions like KVM [15] or software containers [16]. ChameleonCloud [17], CloudLab [18,19] and Grid5000 [20] are examples of bare-metal-as-a-service infrastructure available to researchers. DevOps [[21] ; httermann_devops_2012] addresses 2). Thus, the main challenge with this approach lies in quantifying the performance of the platform in a consistent way. One alternative is to look at the hardware specification and infer performance characteristics from this. As has been shown **[needs-citation]**, this is not consistent. For example, the spec might specify that the machine has DDR4 memory sticks, with a theoretical peak throughput of 10 GB/s, but the actual memory bandwidth could be less (usually is, by a non-deterministic fraction of the advertised performance).

quiho solves this problem by characterizing machine performance using microbenchmarks (Fig. 2). These performance vectors are the "fingerprint" that characterizes the behavior of a machine [22].

This performance vectors, obtained over a sufficiently large set of machines[3], can serve as the foundation for building a prediction model of the performance of an application when executed on new ("unseen") machines [23], a natural next step to take with a dataset like this. As we show in Section 4.4, this is not as good as we would expect.

However, building a prediction model has a utility. If we use these performance vectors to apply SRA and we focus on feature importance [24] of the created models, we can see that they give us fine granularity resource utilization patterns. In Fig. **??**, we show the intuition behind why this is so. The performance of an application is determined by the performance of the subcomponents that get stressed the most by the application's code. Thus, intuitively, if the performance of an application across multiple machines resembles

[3] As mentioned in Section 6, an open problem is to identify the minimal set of machines needed to obtaining meaningful results from SRA.

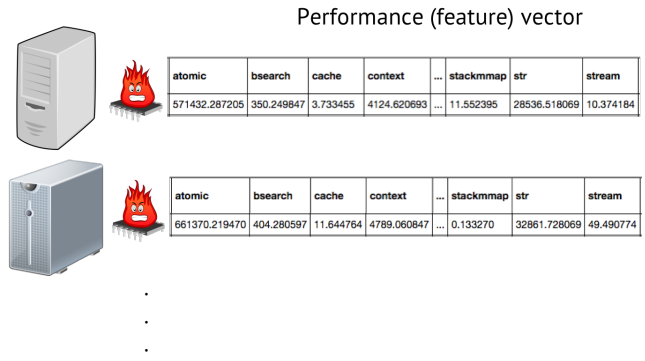

Figure 2: Performance vectors are obtained by executing a battery of microbenchmarks that quantify the performance of multiple subcomponents of a machine.

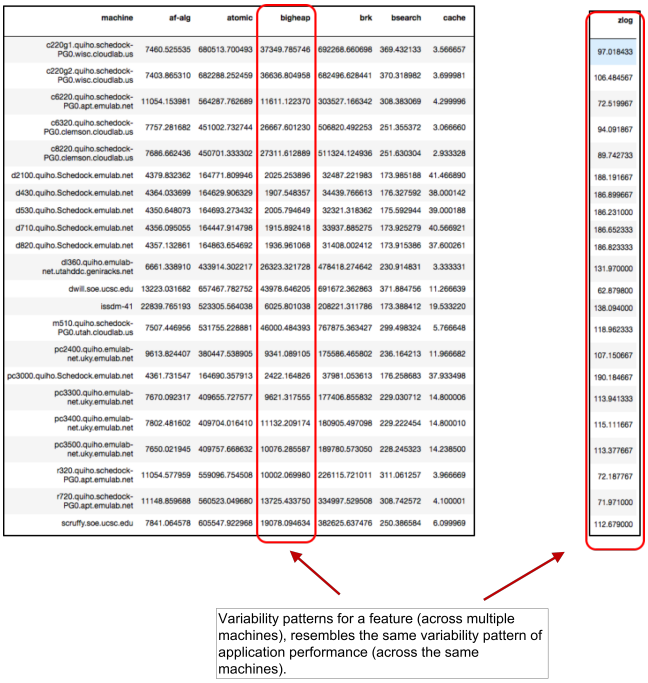

Figure 3: Intuition behind why feature importance implies resource utilization behavior. The variability patterns for a feature (across multiple machines), resembles the same variability pattern of application performance across the same machines. While this can be inferred by obtaining correlation coefficients, proper SRA is needed in order to create prediction models, as well as to obtain a relative rank of feature importances.

the performance of a microbenchmark, then we can say that the application is heavily influenced by that subcomponent.

If we rank features by their relative importance, we obtain what we call a fine granularity resource utilization profile (FGRUP), as shown in Fig. ??.

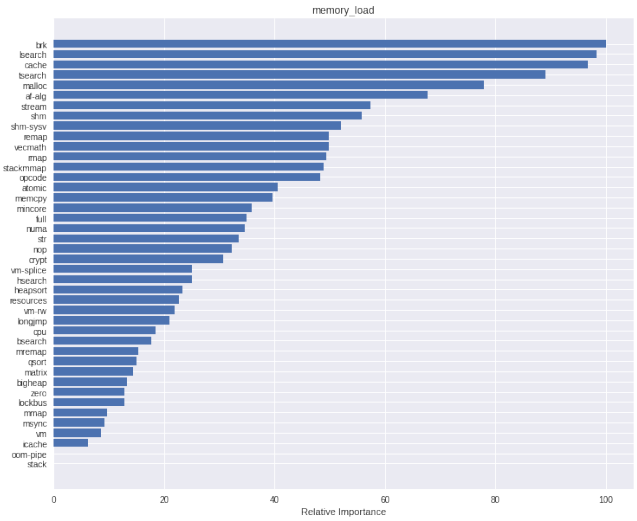

Figure 4: An example profile showing the relative importance of features for a particular application.

In the next section we show how these FGRUPs can be used in automated performance regression tests. Section 4 empirically validates this approach.

3 OUR APPROACH

In this section we do an in-depth description of *quiho*'s approach. We first describe how we obtain the performance vectors that characterize system performance. We then show how using these vectors we can feed SRA to build performance models for an application. Lastly, we describe how we obtain feature importance and how this represent a fine granularity resource utilization profile (FGRUP).

3.1 Performance Feature Vectors As System Performance Characterization

While the hardware and software specification can serve to describe the performance characteristics of a machine, the real performance characteristics can only feasibly[4] be obtained by executing programs and capturing metrics. **`[can we show data for this? or add citation]`** The question then boils down to which programs should we use to characterize performance? Ideally, we would like to have many programs that execute every possible opcode mix so that we measure their performance. Since this is an impractical solution, an alternative is to create synthetic microbenchmarks that get as close as possible to exercising all the available features of a system.

`stress-ng`[5] is a tool that is used to "stress test a computer system in various selectable ways. It was designed to exercise various physical subsystems of a computer as well as the various operating system kernel interfaces". There are multiple stressors for CPU,

[4] One can get generate arbitrary performance characteristics by interposing a hardware emulation layer and deterministically associate performance characteristics to each instruction based on specific hardware specs. While possible, this is impractical (we are interested in characterizing "real" performance).

[5] http://kernel.ubuntu.com/~cking/stress-ng

machine	cpu	cores	num_cpus	threads	vcpus	board_name
\c220g1.quiho.schedock-pg0.wisc.cloudlab.us\"	\"Intel(R) Xeon(R) CPU E5-2630 v3 @ 2.40GHz\"	8	2	2	32	\"UCSC-C220-M4S\"
\c220g2.quiho.schedock-pg0.wisc.cloudlab.us\"	\"Intel(R) Xeon(R) CPU E5-2630 v3 @ 2.40GHz\"	8	2	2	32	\"UCSC-C220-M4S\"
\c6220.quiho.schedock-pg0.apt.emulab.net\"	\"Intel(R) Xeon(R) CPU E5-2450 0 @ 2.10GHz\"	8	1	2	16	\"PowerEdge R320\"
\c6320.quiho.schedock-pg0.clemson.cloudlab.us\"	\"Intel(R) Xeon(R) CPU E5-2660 v2 @ 2.20GHz\"	10	2	1	20	\"PowerEdge C8220\"
\c8220.quiho.schedock-pg0.clemson.cloudlab.us\"	\"Intel(R) Xeon(R) CPU E5-2660 v2 @ 2.20GHz\"	10	2	1	20	\"PowerEdge C8220\"
\d2100.quiho.schedock.emulab.net\"	\"Intel(R) Xeon(TM) CPU 3.00GHz\"	1	1	2	2	\"PowerEdge 2850\"
\d430.quiho.schedock.emulab.net\"	\"Intel(R) Xeon(TM) CPU 3.00GHz\"	1	1	2	2	\"PowerEdge 2850\"
\d530.quiho.schedock.emulab.net\"	\"Intel(R) Xeon(TM) CPU 3.00GHz\"	1	1	2	2	\"PowerEdge 2850\"
\d710.quiho.schedock.emulab.net\"	\"Intel(R) Xeon(TM) CPU 3.00GHz\"	1	1	2	2	\"PowerEdge 2850\"
\d820.quiho.schedock.emulab.net\"	\"Intel(R) Xeon(TM) CPU 3.00GHz\"	1	1	2	2	\"PowerEdge 2850\"
\d1360.quiho.emulab-net.utahddc.geniracks.net\"	\"Intel(R) Xeon(R) CPU E5-2450 0 @ 2.10GHz\"	8	2	2	32	\"ProLiant DL360e Gen8\"
\dwill.soe.ucsc.edu\"	\"Intel(R) Core(TM) i5-2400 CPU @ 3.10GHz\"	4	1	1	4	\"OptiPlex 790\"
\issdm-41.soe.ucsc.edu\"	\"Dual-Core AMD Opteron(tm) Processor 2212\"	2	2	1	4	\"H8DMR-82i\"
\m510.quiho.schedock-pg0.utah.cloudlab.us\"	\"Intel(R) Xeon(R) CPU D-1548 @ 2.00GHz\"	8	1	2	16	\"ProLiant m510 Server Cartridge\"
\pc2400.quiho.emulab-net.uky.emulab.net\"	\"Intel(R) Core(TM)2 Quad CPU Q9550 @ 2.83GHz\"	4	1	1	4	\"Inspiron 530\"
\pc3000.quiho.schedock.emulab.net\"	\"Intel(R) Xeon(TM) CPU 3.00GHz\"	1	1	2	2	\"PowerEdge 2850\"
\pc3300.quiho.emulab-net.uky.emulab.net\"	\"Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz\"	4	1	1	4	\"Inspiron 530\"
\pc3400.quiho.emulab-net.uky.emulab.net\"	\"Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz\"	4	1	1	4	\"Inspiron 530\"
\pc3500.quiho.emulab-net.uky.emulab.net\"	\"Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz\"	4	1	1	4	\"Inspiron 530\"
\r320.quiho.schedock-pg0.apt.emulab.net\"	\"Intel(R) Xeon(R) CPU E5-2450 0 @ 2.10GHz\"	8	1	2	16	\"PowerEdge R320\"
\r720.quiho.schedock-pg0.apt.emulab.net\"	\"Intel(R) Xeon(R) CPU E5-2450 0 @ 2.10GHz\"	8	1	2	16	\"PowerEdge R320\"
\scruffy.soe.ucsc.edu\"	\"Intel(R) Xeon(R) CPU E5620 @ 2.40GHz\"	4	1	2	8	\"XBDTG-QF\"

Figure 5: List of different type of machines available on Cloudlab.

CPU cache, memory, OS, network and filesystem. Since we focus on system performance bandwidth, we execute the (as of version 0.07.29) 42 stressors for CPU, memory and virtual virtual memory stressors. A *stressor* is a function that loops a for a fixed amount of time (i.e. a microbenchmark), exercising a particular subcomponent of the system. At the end of its execution, `stress-ng` reports the rate of iterations executed for the specified period of time (referred to as `bogo-ops-per-second`).

Using this battery of stressors, we can obtain a performance profile of a machine (a performance vector). When this vector is compared against the one corresponding to another machine, we can quantify the difference in performance between the two at a per-stressor level. Every stressor (element in the vector) can be mapped to basic features of the underlying platform. For example, `stream` to memory bandwidth, `zero` to memory mapping, `qsort` to sorting data, and so on and so forth. However, the performance of a stressor in this set is *not* completely orthogonal to the rest. Fig. 6 shows a heat-map of Pearson correlation coefficients for performance vectors obtained by executing `stress-ng` on all the distinct machine configurations available in CloudLab [19] (Fig. 5 shows a summary of their hardware specs). As the figure shows, some stressors are slightly correlated (those near 0) while others show high correlation between them (in Section 4.4 we apply principal component analysis to this dataset).

3.2 System Resource Utilization Via Feature Importance in SRA

SRA is an approach for modeling the relationship between variables, usually corresponding to observed data points [25]. One or more independent variables are used to obtain a *regression function* that explains the values taken by a dependent variable. A common approach is to assume a *linear predictor function* and estimate the unknown parameters of the modeled relationships.

A large number of procedures have been developed for parameter estimation and inference in linear regression. These methods differ in computational simplicity of algorithms, presence of a closed-form solution, robustness with respect to heavy-tailed distributions, and theoretical assumptions needed to validate desirable statistical properties such as consistency and asymptotic efficiency. Some of

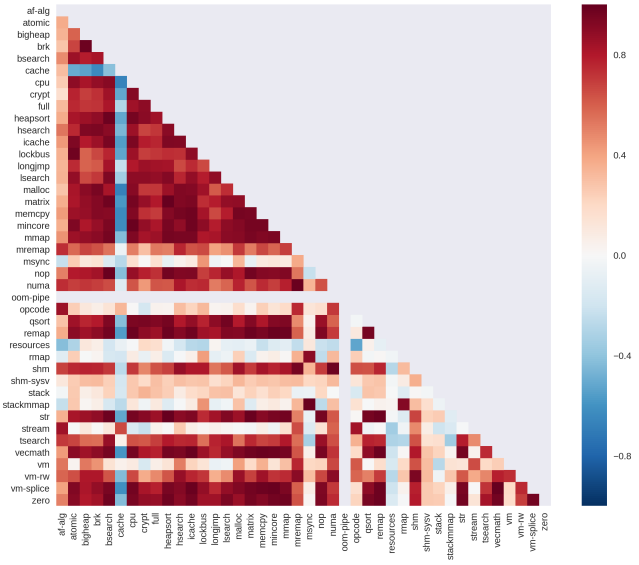

Figure 6: heat-map of Pearson correlation coefficients for performance vectors obtained by executing `stress-ng` on all the distinct machine configurations available in CloudLab.

the more common estimation techniques for linear regression are least-squares, maximum-likelihood estimation, among others.

`sklearn` [26] provides with many of the previously mentioned techniques for building regression models. Another technique available is gradient boosting [27]. Gradient boosting is a machine learning technique for regression and classification problems, which produces a prediction model in the form of an ensemble of weak prediction models, typically decision trees [28]. It builds the model in a stage-wise fashion like other boosting methods do, and it generalizes them by allowing optimization of an arbitrary differentiable loss function. This function is then optimized over function space by iteratively choosing a function (weak hypothesis) that points in the negative gradient direction. Fig. 7 shows the process applied to obtain FGRUPs for an application. In the next section we evaluate their effectiveness.

4 EVALUATION

In this section we answer:

- can FGRUPs accurately capture application performance behavior?
- can FGRUPs work for identifying simulated regressions?
- can FGRUPs work for identifying real-world regressions?

This paper adheres to The Popper Experimentation Protocol[6] [29], so experiments presented here are available in the repository for this article[7]. Experiments can be examined in more detail, or even re-executed, by visiting the `[source]` link next to each figure. That link points to a Jupyter notebook that shows the analysis and source code for that graph, which points to an experiment and its artifacts.

[6] http://falsifiable.us
[7] http://github.com/ivotron/quiho-popper

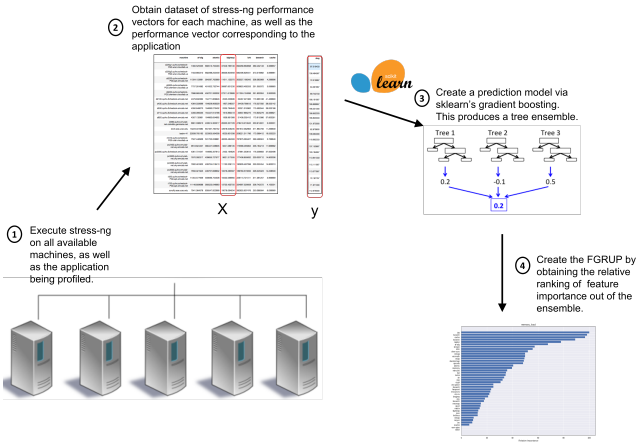

Figure 7: The workflow applied in order to obtain FGRUPs.

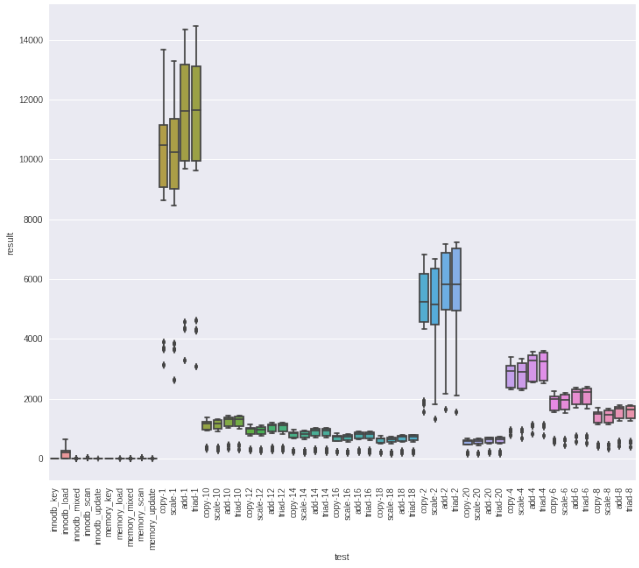

Figure 8: Variability.

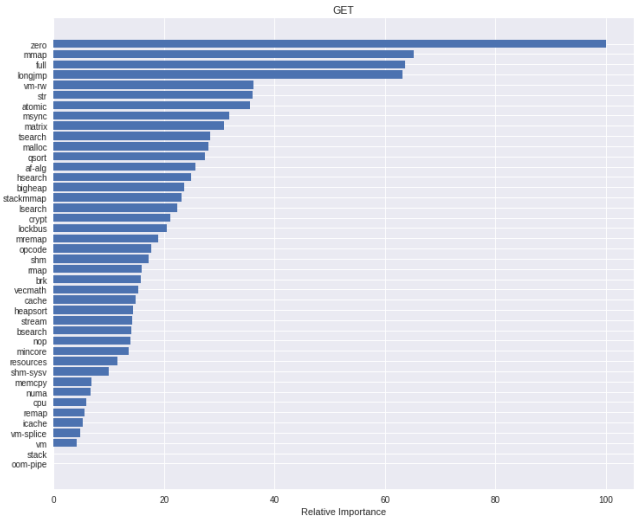

Figure 9: redis.

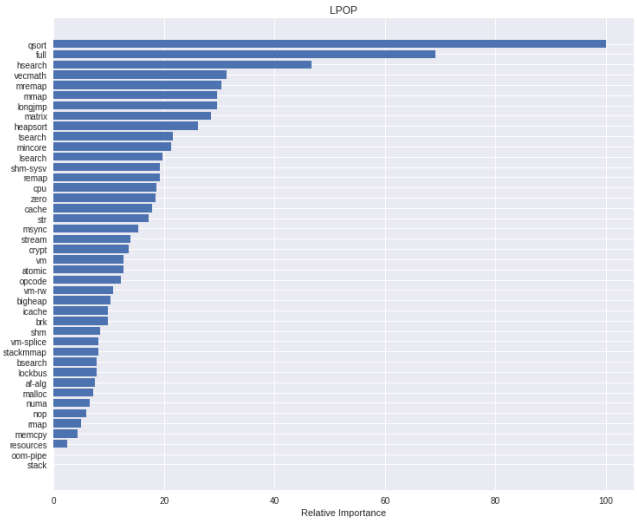

Figure 10: redis lpop.

4.1 Performance Profiles

We show they actually show the performance of known benchmarks.

Methodology - For every workload:

1. Discover relevant features using quiho.
2. Analyze code to corroborate that discovered features are indeed the cause of performance differences.

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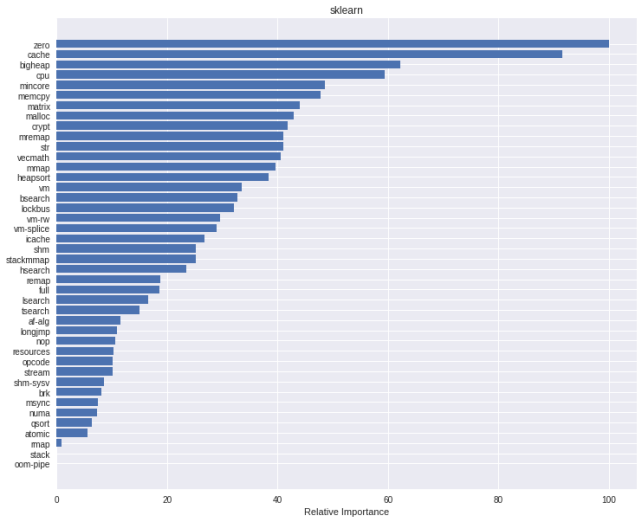

Figure 11: sklearn

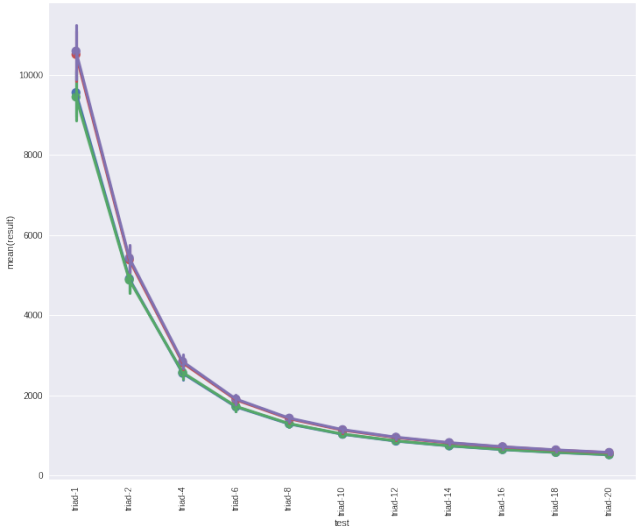

Figure 12: stream cycles

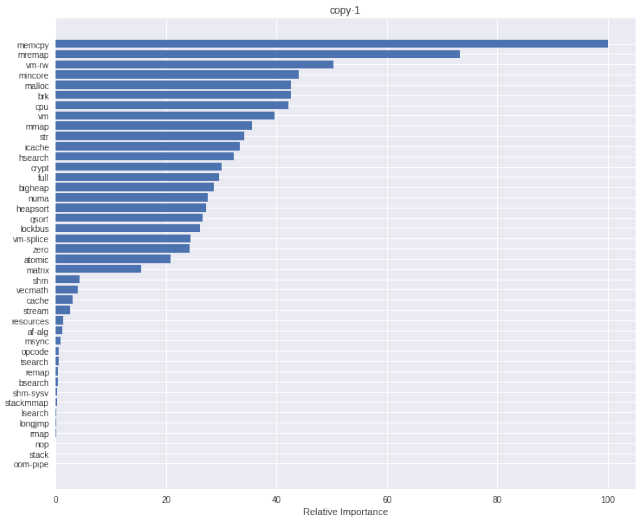

Figure 13: stream copy-1

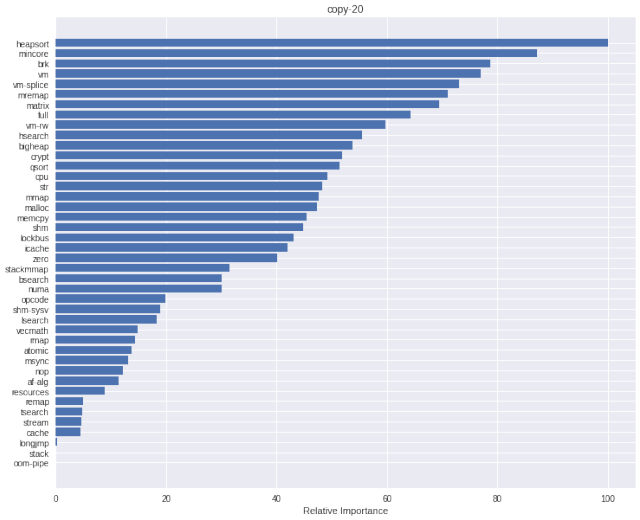

Figure 14: stream copy-20

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4.2 Simulating Regressions

We show that if we simulate regressions, then *quiho* identifies them correctly.

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text in between "Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

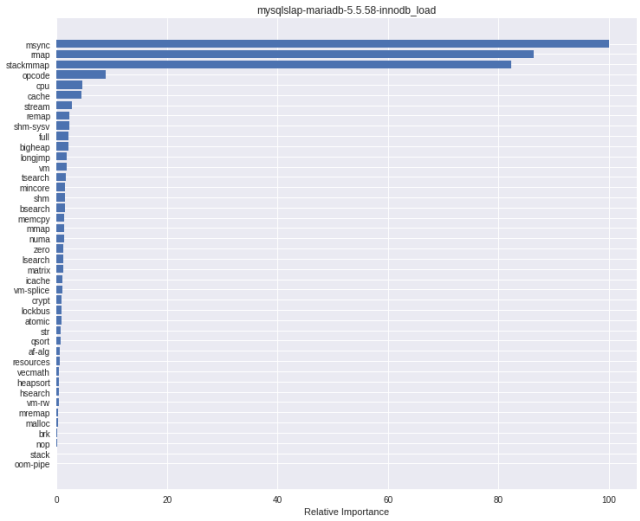

Figure 15: mariadb-5.5.58.

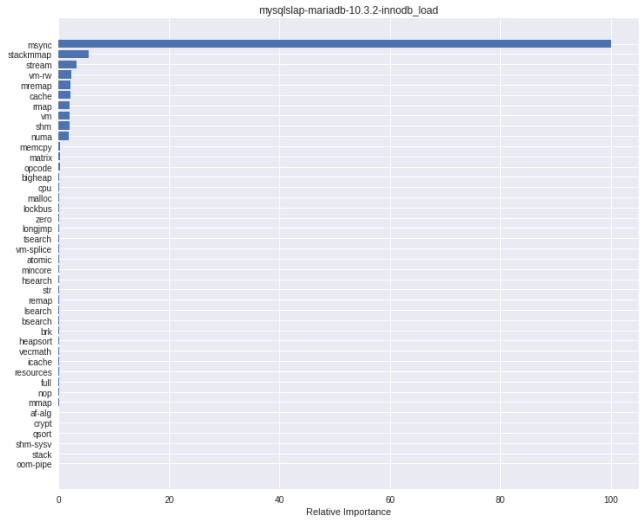

Figure 16: mariadb-10.0.3

mariadb innodb.

"Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

mariadb memory.

Due to lack of space we can not include the remaining benchmarks. In total, we have 10 benchmarks for which we can induce several performance regressions, for a total of 30 performance regressions.

4.3 Real-world Scenario

We show that *quiho* works with a real software project.

Use of FGRUPs: FGRUPs aid in performance engineering. When analyzing any performance degradation of an application, then the feature importance can be used as a pointer to where to start with the investigation. For example, if *memorymap* ends up being the most important feature, then we can start by looking at any code/libraries related to this functionality, or looking at corresponding performance counters (if available). In this case, we would look for the code.

Due to lack of space, we cannot present results for 5 other applications where we detect regressions successfully. These are ZLog, Apache Commons Math, GCC, PostgresSQL, Redis, Apache Web Server and MongoDB.

4.4 *quiho* cannot predict performance

We show how *quiho* does not do a good job at predicting performance.

text in between

text in between

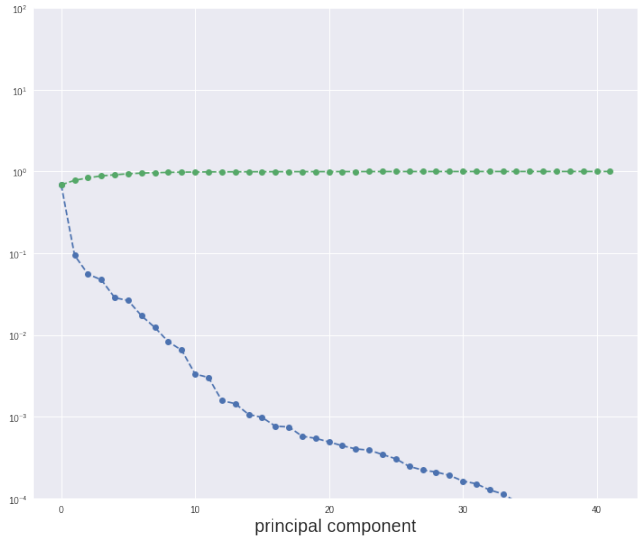

Figure 17: Variability reduction per subcomponent in PCA.

5 RELATED WORK

5.1 Anomaly Detection and Bottleneck Identification

It's been used in bottleneck detection [8]. **TODO: mention briefly how it is used**.

5.2 Automated Regression Testing

In [13], they use it to detect regressions using a dataset of performance counters.

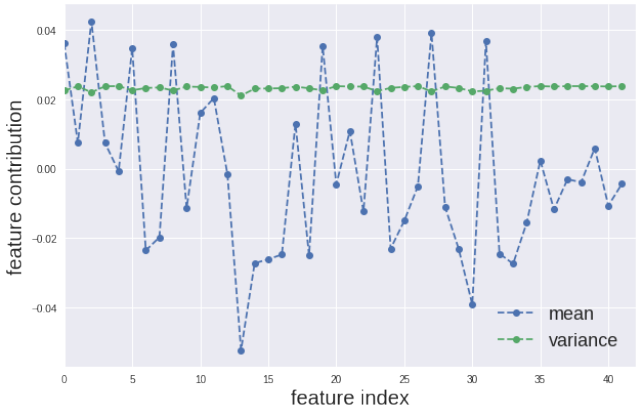

Figure 18: Variability reduction per index.

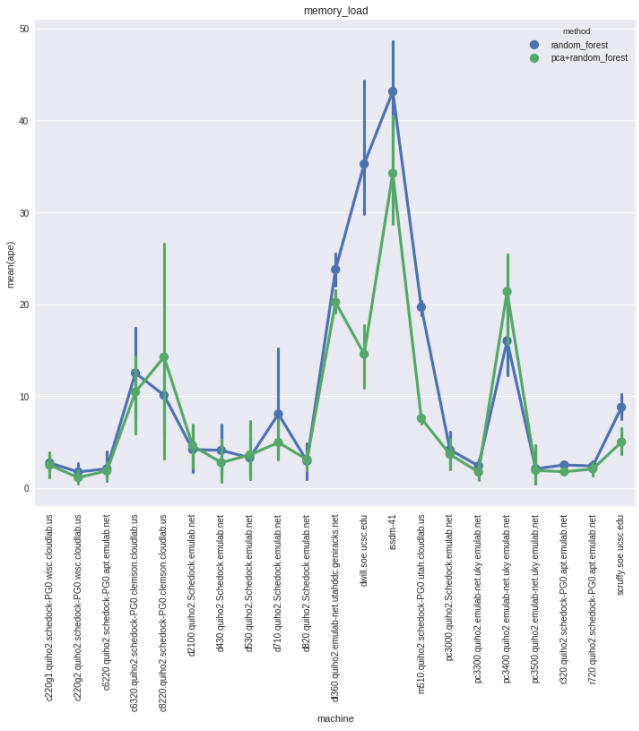

Figure 19: Mean Absolute Percentage Error of cross-validation.

6 CONCLUSION AND FUTURE WORK

- Main draw-back of this technique is that we need to run on multiple machines.
- We used `stress-ng` but this is not the only thing we can use. Ideally, we would extend this battery of tests so that we have more "coverage" of the distinct subcomponents of a system.

In the not-so-distant future:

- multi-node
- minimum number of machines?
- single machine?
- long-running (multi-stage) applications. e.g. a web-service or big-data application with multiple stages. In this case, we would define windows of time and we would apply quiho to each. The challenge: how do we automatically get the windows rightly placed.

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