SPEC OPEN SYSTEMS GROUP

CLOUD COMPUTING WORKING GROUP

Report on Cloud Computing to the OSG Steering Committee

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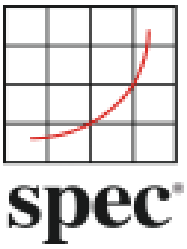

Introduction and Objectives

With Cloud Computing on the rise, there is a need to monitor and measure the performance of cloud systems. To address this issue, SPEC started two separate working groups to investigate this area: one under the Research Group (RG) and the second under the Open Systems Group (OSG). This document covers the investigations and recommendations from the OSGCloud working group.

The OSGCloud working group was formed with the main goal to research and recommend application workloads for cloud computing in collaboration with other osg sub-committees and the Research working group. The list of goals included the following:

- Help develop a cohesive cloud picture for OSG.
- Develop a consensus definition of cloud computing.
- Identify where the working group fits within the OSG spectrum.
- Collaborate with OSG sub-committees to define the cloud picture.
- Recommend a common framework for cloud benchmarks.
- Investigate potential cloud metrics and identify which metrics are most relevant for various SPEC benchmarks.
- Create a set of guidelines for OSG subcommittees to use when they create benchmarks in the cloud computing context.
- Determine and recommend application workloads for cloud computing.

In contrast, the RG Cloud Group takes a broader approach relevant for both academia and industry. Benchmarks developed by this group are intended to be used to gain larger understanding of Cloud behavior and performance. The main goal of research benchmarks is to provide representative application scenarios, defined at a higher level of abstraction that can be used as a basis to evaluate early prototypes and research results as well as full-blown implementations of Cloud platforms.

EXECUTIVE SUMMARY

The OSG Cloud Working Group investigated its assigned goals from April 2011 to February 2012. The group based its definition and industry conventions on the NIST Cloud Computing publication, originally published as a draft, and ultimately a final document in September 2011. From this base, the Working Group has identified three classes of interested parties to Cloud benchmark results: Hardware/Software-Vendors, Cloud-Providers and End-Consumers. These three parties form two distinct relationships which define two types of benchmarks: Black Box and White Box. These two benchmark types have both conflicting and common requirements, which are highlighted throughout the document. We identified Cloud Computing specific metrics and define them in Section 3. Some Cloud metrics will have benchmark specific variations, while others remain constant across all benchmarks. Section 4.1 and 4.2 contain some initial steps to consider when converting a benchmark to run in a Cloud.

The OSGCloud members recommend the following:

1) Creation of an OSG Cloud subcommittee with an initial charter described in Section 6.1.

1 Cloud Computing

1.1 Definition of the Cloud

We adopted the definition of cloud computing from the NIST Special Publication No. 145 [(Mell & Grance, 2011)], which defines Cloud Computing as:

> Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.[1]

Three roles exist within cloud computing. ***Cloud-Providers*** sell computing or software services purchased by the ***End Customer/Consumer***. A ***Cloud-Provider*** builds its cloud using products from various ***Hardware*** and ***Software Vendors***. See Section 1.2 (Interested parties of a Cloud Benchmark) for a more detailed discussion.

The NIST document describes five essential cloud characteristics, three service models, and four deployment models. We briefly describe these below, based on the NIST document.

1.1.1 Characteristics

Cloud Computing has five essential characteristics, namely:

1. **On-demand self-service**, where a consumer can provision compute and storage capabilities without requiring human intervention from provider.
2. **Broad network access**, where a consumer can access compute and storage capabilities over the network.
3. **Resource pooling**, where a provider groups together resources such as CPU, memory, disk, and storage to serve multiple consumers.
4. **Rapid elasticity**, where resources used can be rapidly and in some cases automatically increased or decreased to handle demand.
5. **Measure service**, where the service used a consumer is metered.

[1] The definition does not mandate the use of virtualization for a Cloud.

1.1.2 Service Models

There are three service models for cloud computing. They affect the definition of a **System Under Test** (**SUT**) for any cloud benchmarks. The following are a brief description of the service models.

Infrastructure as a Service (IaaS) The ***Service Provider*** gives the ***End-Consumer*** the capability to the provision processing, storage, network, and basic computing resources. They can also deploy and run arbitrary operating systems. The ***End-Consumer*** does not manage or control the underlying physical cloud infrastructure, but has control over the operating system, assigned storage, deployed applications, and limited control of select networking components (e.g., host firewalls).

Platform as a Service (PaaS) The ***Service Provider*** gives the ***End-Consumer*** the capability to deploy consumer-created or acquired applications created using programming, languages, libraries, services, and tools supported by the ***Service Provider***. The ***Service Provider*** retains control and manages the underlying cloud infrastructure, including network, servers, operating systems, and physical storage. ***End-Consumer*** has control over the deployed applications and configuration settings for the application-hosting environment.

Software as a Service (SaaS) The ***Service Provider*** gives ***End-Consumer*** the capability to use the provider's applications running on a cloud infrastructure. The applications are accessible from various client devices through either a thin client interface, such as a web browser (e.g., web-based email), or a program interface. The ***Service Provider*** retains control and manages the underlying cloud infrastructure, including individual applications, these application configurations, network, servers, operating systems, and physical storage. The ***End-Consumer*** might have limited control of user-specific application configuration settings.

1.1.3 Deployment Models

The NIST document defines four deployment models, namely,

Private cloud The cloud is configured for exclusive use by one or more organizations.

Public cloud The cloud is configured for use by the general public.

Hybrid cloud The cloud is a composition of distinct infrastructures in order to retain the proprietary technology by the consumer.

Community cloud The cloud is provisioned for exclusive use for a community of consumers.

1.2 Interested parties of a Cloud Benchmark

There are at least three categories interested in the development and use of a cloud benchmark. Between these three parties exists two relationship types.

1.2.1 Participants

The three identified parties are:

Cloud-Providers build data centers using standard hardware, network, and management software. Amazon, IBM, HP, VMWare, Microsoft, Oracle and Terremark are examples of companies that provide public or enterprise IaaS, Paas or SaaS clouds. They will be interested in publishing the benchmark results of their service offerings. They would also be interested in the benchmark results of hardware, software or network vendor products, and how these components support the performance of their service.

Hardware and Software Vendors provide the hardware (computers, blades, or servers) and software (virtualization, management, automation) products used to build the cloud. AMD, HP, Intel, IBM, VMWare, OpenStack, Oracle, Red Hat, and VMware are examples of companies that might publish benchmark results for their customers.

End-Consumers cloud customers might use cloud benchmark results to help select a Cloud-Provider. These are primarily businesses. While there exist several collaboration and social apps used by individuals, the recommendations in this document will not address the needs of this community. We restrict our attention to business users of the cloud.

1.2.2 Cloud Benchmark Audience Types

Based on the above, use of cloud benchmarks fall into two broad categories:

White Box benchmark disclosures Published by one or more ***Hardware/Software Vendors*** and used by ***Cloud-Providers*** to determine the right set of hardware and software products to deploy in their cloud. ***Cloud-Providers*** can also publish results of the hardware and software components used in their cloud.

Black Box benchmark disclosures Published by ***Cloud-Providers*** and used by ***End-Consumers*** to determine the appropriate cloud service provider for their application needs.

DIFFERENCES

A given workload can be tested either in the black-box or white-box context. Each has differing implications for reporting and comparability, usually addressable by the Run Rules defined for the released benchmark.

White Box Benchmark The SUT's exact engineering specifications is known and under the control of the tester. The benchmark results allow full comparisons, similar to existing benchmark results.

Black Box Benchmark

The ***Cloud-Provider*** provides a general specification of the SUT, usually in terms of how the ***End-Consumer*** may be billed. For example, an end user of a cloud may rent a cloud platform under the description of "*2 compute units*." The exact hardware details corresponding to these compute units may not be known. Due to this vagueness or incompleteness, comparing benchmark results requires additional information not currently collected or mandated. For example, the benchmark disclosure may include additional conditions, such as time and place where measurements were collected, or dynamic changes to the SUT during the collection period.

1.3 Cloud Computing Use Cases

The OSG Working Group identified general classes of computing and mapped these to the Research Group's processing types.

1.3.1 Computing Use Cases

The general class of applications either use cloud computing infrastructure or might transition all or subsets to cloud computing. See Appendix A for more details on services and usage of each type.

Social Networking Users access web servers to exchange messages with others, update information, view recommendations or endorsements, and otherwise interact with other users, both in real time and not.

The CloudBench/Olio benchmark currently simulates this collection of web server activities, and scales by controlling the number of concurrent users.

Collaboration A group of users share the same view and access into a data set. Access can be through standard web browsers, custom plug-ins, or proprietary client software.

Mail / Messaging Private business e-mail servers can be easily moved to outsourced e-mail services. Some of these companies run on private or public infrastructure clouds. More sophisticated e-mail services or a portal site will interface with social networking, calendar services, 3rd party remote services, user profiling (for targeted ads), and other non-e-mail things,

Data Analytics Many companies and groups are using the large clusters of hosts to evaluate large data sets (log files; personal information; user comments on shows, books, or events; interesting conversations), or extract sophisticated findings from multi-layered data sets, with complex relationships.

Data Warehousing / Mining This computing category builds on large sets of both structured and unstructured data for later use by other types.

NoSQL Databases These non-relational databases can support peta-byte scale data sets, distributed across hundreds to thousands of machines. They are used where '*weak consistency guarantee*' policies suffice. Real-time web applications, document databases, graph databases, key-value data stores are among some current applications of this technology.

Business OLTP This long-standing processing type is characterized by high data I/O volumes and well defined data sets. Both real-time and scheduled processing exist.

Memory Cloud A group of machines maintain a coherent and shared data space used by many other types. It is typically used by multi-layered software, that also have latency requirements.

HPC **High-performance computing (HPC)** uses supercomputers and computer clusters to solve advanced computation problems. This genre of workloads also includes engineering, simulation, graphics and data applications that run on cluster-based systems.

On-line Gaming Similar to social networking or collaboration, but also maintain time-sensitive services

Streaming Audio/Video An increasing number of consumers access music, books, or videos from various media distribution companies.

Voice over IP Digital VoIP services are replacing and expanding audio communications for many consumers and companies. This includes both audio and video transmissions across the Internet, with stringent latency and computational needs.

1.3.2 Use Case to Customer Map

The following table identifies potential customers. It identifies companies or industries known to use the Research Group's processing types. The OSG Working Group also polled members and other interested parties as to the usefulness or criticality of a cloud benchmark in this processing category.

Processing Types	Potential Audience	Survey Score
Social Networking	LinkedIn, Facebook, Twitter, Yelp, Googleplus, Groupon, Goodreads, Netflix (Social net component), Amazon (Social net component), Workpress	3
Collaboration	WebEx Screen sharing, Citrix GoToMeeting, Skype, Microsoft Live Meeting	
Mail / Messaging	Cloud providers, existing Internet Service providers (AOL, cable operators, internet portals), E-mail Outsourcing providers, e-mail filtering services, Mid to large sized companies.	3.43
Data Analytics	Cloud providers, SaaS providers, mobile phone companies	4.43
Data Warehousing / Mining	Cloud providers,	4
NoSQL Databases	Amazon, Facebook, Twitter, Yahoo, Digg, Hadoop users	2.44
Business OLTP	Business users of databases, enterprises	3.56
Memory Cloud	Web Service users, Social Network users	3
HPC	Cloud service providers	
On-line Gaming	Game providers, Cloud providers for games; Government, military	2.57
Streaming audio/video	TV networks, Apple TV, Google TV, Internet Radio, Netflix, iTune, YouTube, Online Universities	
VOIP	SPEC SIP customers,	

1.3.3 Use Case to Processing Type Map

The following table shows which (Research Group's) Processing Type is present in each Cloud Computing Use Case.

Process Type \ Cloud Use Case	Social Networking	Collaboration	Mail / Messaging (IM, Tweets)	Data Analytics	Data Warehousing / Mining	NoSQL Databases	Business OLTP	Memory Cloud	HPC	On-line Gaming	Streaming audio/video	VOIP
Data-Intensive / Planned Batch Jobs	×		×	×	×	×	×	×	×	×		
Processing Pipelines	×		×	×	×				×	×		×
Dynamic Websites	×									×		
Business Processing / OLTP / Mission Critical applications				×		×	×		×			
Latency Sensitive		×	×			×	×			×	×	×
Application Extensions / Backends for Mobile Communications		×	×	×						×	×	
Bandwidth and Storage Intensive		×	×	×	×	×	×	×	×	×	×	×
Mail Applications			×									
Others			×	×								

1.4 Existing Cloud Frameworks

The Research cloud working group has summarized a list of publicly available cloud benchmarks. http://research.spec.org/en/benchmarking-portal/links.html. The OSG Cloud Working Group presents the following as some of the better known and available cloud benchmarks.

Benchmark	Features	Source
YCSB	– Evaluate performance of key-value based databases – Measures Elasticity	Yahoo! Research at http://research.yahoo.com/Web_Information_Management/YCSB

Benchmark	Features	Source
Cloudstone / Olio	– Workloads: Web 2.0, MySQL, PostgressSQL, and Memcached – By default, runs against Amazon EC2 but has instructions on how to set up in other clouds	Berkeley RAD Lab project at http://radlab.cs.berkeley.edu/wiki/Projects/Cloudstone
Malstone	– Distributed, data intensive computing workload, using synthetic data to determine infection rates by website to its visitors.	Open Cloud Consortium project at http://code.google.com/p/malgen/
Hadoop	– Several workload types: cpu, map reduce, machine learning, parallel computation, distributed file system, and distributed databases – Used by many 3rd party benchmarks – No strict Run Rules	Open source project at http://hadoop.apache.org
Cloud Harmony	– Measure performance of black box cloud deployments using various workloads – Offers comparison of various benchmark results as a paid service	http://www.CloudHarmony.com

2 Benchmark Considerations

2.1 What is a Cloud SUT?

Defining SUT for a cloud benchmark is challenging due to conflicting goals of interested parties and different cloud service models. As discussed in earlier sections, an ***End-Consumer*** does not have knowledge of the physical infrastructure for **IaaS**, **PaaS**, or a **SaaS** service. However, ***Hardware and Software Vendors*** are one of the interested parties in a cloud benchmark. In order for a cloud benchmark to have any useful meaning for these vendors, the physical infrastructure should also be part of the results that a cloud benchmark reports. However, mandating the reporting of physical infrastructure results is problematic, because it will exclude benchmarking many existing public Cloud-Providers.

The ***System Under Test*** (SUT) comprises all components (cloud service, hardware, software, network connections within the SUT, and support services which are being tested by the cloud workload or required by the specific benchmark run rules. It does not include any client(s) or driver(s) necessary to drive the cloud workload or the network connections between the driver(s) and SUT.

By existing SPEC benchmark convention, the ***System Under Test*** (SUT) comprises all components (cloud service, hardware, software, network connections within the SUT, and support services which are being tested by the cloud workload or required by the specific benchmark run rules. It does not include any client(s) or driver(s) necessary to generate the cloud workload, nor the network connections between the driver(s) and SUT.

Mandating the disclosure of the physical infrastructure presents many problems due to the conflicting goals of interested parties and different cloud service models. ***Hardware and Software Vendors*** provide benchmark results to their, the ***Cloud-Providers***, who derive the most useful meaning through the detailed description of the physical infrastructure and the corresponding results. However, an ***End-Consumer*** has little to no knowledge of the ***Cloud-Provider***'s physical infrastructure for **IaaS**, **PaaS**, or a **SaaS** service. Providing such a detailed description is impossible without a ***Cloud-Provider***'s cooperation. Therefore, a mandate that reports must include the details of the physical infrastructure is problematic, because it will exclude benchmarking many existing public Cloud-Providers.

2.2 SUT Components

The actual set of **SUT**'s constituent pieces differs based on the relationship between the SUT and the tester.

Black Box Cloud

The SUT consists of a description of the specific cloud offering used to run the workload with sufficient detail to meet Full Disclosure Report (FDR) Requirements as described in Section 2.3 and the specific benchmark's reproducibility requirements on and instance of the same offering.

White Box Cloud

The SUT description can be more specific, similar to many existing SPEC benchmarks. These SUT descriptions consist of:

- The host system(s) (including hardware and software) required to support the Workload and databases.
- All network components (hardware and software) between host machines which are part of the SUT and all network interfaces to the SUT.
- Components which provide load balancing within the SUT.
- All software that is required to build, deploys, and run the specific benchmark workload.

Comment 1

Any components which are required to form the physical TCP/IP connections (commonly known as the NIC, Network Interface Card) from the host system(s) to the client machines are considered part of the SUT.

Comment 2

A basic configuration consisting of one or more switches between the Driver and the SUT is not considered part of the SUT. However, if any software/hardware is used to influence the flow of traffic beyond basic IP routing and switching, it is considered part of the SUT. For example, when DNS Round Robin is used to

implement load balancing, the DNS server is considered part of the SUT and therefore it must not run on a driver client.

2.3 Full Disclosure Report (FDR) Requirements

For both ***Black Box*** and ***White Box*** cloud types, the ***Full Disclosure Report*** (FDR) must include a detailed description of the SUT, often referred to as a *'Bill of Materials*' (BOM). The intent of the BOM is to enable a reviewer to confirm that the tested configuration satisfies the run rule requirements and to document the components used with sufficient detail to enable a customer to reproduce the tested configuration and obtain pricing information from the supplying vendors for each component of the SUT.

The SUT description or BOM must reflect the level of detail a customer would see on an itemized bill. It should list individual items in the SUT that are not part of a standard package. For each item, the BOM should include the item's supplier, description, the item's ID (the code used by the vendor when ordering the item), and the quantity of that item in the SUT.

For example, a black box SUT for Amazon EC2 may be described as:

Supplier: Amazon
Description: Small vm with
1.7 GB memory
1 EC2 Compute Unit (1 virtual core with 1 EC2 Compute Unit)
160 GB instance storage
32-bit platform

I/O Performance: Moderate
Region: US East coast
Zone: portion with region where VM is hosted
https://aws.amazon.com/ec2/instance-types/

ID: API name: m1.small
Quantity: 1 (collocation details if the quantity is greater than 1)
Date and time of use:

An example of a ***White Box*** description may be similar to the one here:

http://www.spec.org/jEnterprise2010/results/res2011q3/jEnterprise2010-20110727-00023.html#bill_of_materials

Supplier	Description	Product #	Qty
Application Server			
Oracle	Sun Blade X6270 M2 Base Assembly	X6270-AB	1
Oracle	3.46GHz Intel 6-Core Xeon X5690	X6270-AA-16H3460	2
Oracle	4GB Registered DDR3-1333 DIMM	4910A	12
Oracle	Memory filler panel	5879A-N	6
Oracle	300GB - 10K RPM SAS Disk	RB-SS2CF-300G10K2	4
Oracle	6Gbps SAS-2 RAID Expansion Module	SG-SAS6-R-REM-Z	1
Oracle	Premier Support for Systems 3 years	Q-PREM-SPRT-SYS	1
Database Server			
Oracle	Sun Blade X6270 M2 Base Assembly	X6270-AB	1
Oracle	3.46GHz Intel 6-Core Xeon X5690	X6270-AA-16H3460	2
Oracle	8GB Registered DDR3-1333 DIMM	4911A	18
Oracle	2.5in HDD Filler Panel	6331A-N	2
Oracle	Sun Storage 6180 Array	TA6180R11A2-O-N	2
Oracle	300 GB - 15000 rpm FC-AL HDD	TC-FC1CF-300G15K-N	32
Oracle	6Gbps SAS-2 RAID Expansion Module	SG-SAS6-R-REM-Z	1
Oracle	Premier Support for Systems 3 years	Q-PREM-SPRT-SYS	1
Blade Server Enclosure			
Oracle	Sun Blade 6000 Modular System	A90-D	1
Oracle	Dual 10GbE 10GBE SFP+ PCIe Express Module	X1110A-Z	3
Oracle	10 GigE Dual Rate SFP+ SR Transceiver, MMF	2129A	6
Oracle	8GB PCI-E Dual FC/GbE Host Adapter EM	SG-XPCIEFCGBE-Q8-N	1
Oracle	Power cord, QTY4, AC Input 20A		1
Oracle	Premier Support for Systems 3 years	X5074A-Z-N Q-PREM-SPRT-SYS	1
Oracle	Oracle Linux Basic Support for 3 years		2
Oracle	Oracle Database 11g Enterprise Edition, Per Processor Unlimited Users for 3 years		6*
Oracle	Partitioning, Per Processor Unlimited Users for 3 years		6*
Oracle	Oracle Premium Support for 3 years		2
Oracle	Oracle WebLogic Server Standard Edition Release 10.3.5 Per Processor for 3 years		6*
Oracle	Oracle Premium Support for 3 years		1

(* 6 = 0.5 * 12) Explanation: For the purposes of counting the number of processors which require licensing, a multicore chip with 'n' cores shall be determined by multiplying 'n' cores by a factor of 0.5

3 Relevant Cloud Metrics

Metrics are used as the measurement criteria for the tests. The following metrics have been identified as being the key indicators of performance for most workloads in a Cloud environment. **Note**: Due to the breadth of cloud implementations, not all metrics will be applicable to each benchmark. For instance, if ***End-Consumer*** tests a public cloud, the density and power metrics are typically not measurable.

The key metrics identified are:

- Elasticity, which consists of at least the following components
  - Provisioning Interval
  - Agility
  - Scaleup/Down
  - Elastic speedup
- Throughput
- Response time
- Variability

Other relevant metrics include:

- Durability
- Reliability
- Power
- Price
- Density

The nature of the cloud makes these metrics, while relevant, difficult to measure in the context of benchmarking. These metrics also do not represent quantifiable engineering metrics.

3.1 Elasticity

Elasticity has become a key component and buzz word when talking about cloud services. The term has become synonymous with how quickly a service can adapt to the changing needs of the customer. Thus, a highly elastic system can scale to include newer instances, as well as quickly provision those instances. Based on this, we define two metrics to characterize the term Elasticity.

The exact definitions of the metrics captured under Elasticity will vary based on the service model and SUT definition.

Provisioning interval

Provisioning Interval is defined as the time needed to bring up or drop a resource. This is the time between initiating the request to bring up a new resource or to relinquish it, and when the resource is either ready to serve the first request or when it serves the first request. The state of the new instance will have to be

defined and disclosed by individual benchmarks. For example, the state may include all the necessary operating system and database server patches. Or state complies with specialized workload requirements, as in the case of IaaS.

EXAMPLES OF *PROVISIONING INTERVAL* METRICS BY PLATFORM

IaaS	The measured time needed to bring up a new instance, or add more resources (like cpu or storage) to existing instance.
PaaS	The measured time needed to bring up a new instance of an application server (example: Microsoft Azure, or Java Enterprise), or to bring up Hadoop datanode and tasktracker servers on the new cluster nodes (which could be virtual machines).
SaaS	The measured time needed to bring new Application instances on-line to meet increasing demand (moving from 10000 to 20000 concurrent users).

Agility

This metric characterizes the ability to scale the workload and the ability of a system provisioned to be as close to the needs of the workload as possible.

One way to define this quantity would be as

$$\sum_{i=0}^{N} | \, Cap\_prov(i) - Cap\_min(i) \, |$$

Where

Cap_min(i)	The difference between the minimum capacity needed to meet the QOS at a given workload level for an interval *i*.
Cap_prov(i)	The recorded capacity provisioned for interval *i*.
Excess(i)	The excess capacity for interval *i* as determined by *Cap_prov(i) – Cap_min(i),* when Cap_prov(i) > Cap_min(i) and zero otherwise.
Shortage(i)	The shortage capacity for interval I is determined by Cap_min(i) – Cap_prov(i), when Cap_min(i) > Cap_prov(i) and zero otherwise.
N	The total number of data samples collected during the measurement period

Agility maintained over a period can be defined as

$$\frac{\sum_{i=0}^{N} \text{Excess(i)}}{\sum_{i=0}^{N} \text{Cap\_min(i)}} + \frac{\sum_{i=0}^{N} \text{Shortage(i)}}{\sum_{i=0}^{N} \text{Cap\_min(i)}}$$

For an ideal system, this number should be as close to zero as possible.

This is a measurement of the ability to scale up and down while maintaining a specified QOS. The above definition will not be valid in a context where the QOS is not met.

Scaleup/Down

Scaleup/down is defined as measurements of the system's ability to maintain a consistent unit completion time when solving increasingly larger problems only by adding a proportional amount of storage and computational resources—i.e., if we double the resources, can we solve a problem twice as large? [(Toward a Standard Benchmark for Computer Security Research, 2011)]

SCALE UP/DOWN EXAMPLE:

1. Create an 8-node (1 master, 8 slaves) Hadoop cluster, and run Terasort . Measure the Terasort completion time, *T8*.
2. Create a 16 node (1 master, 16 slaves) Hadoop cluster, and run Terasort. Measure Terasort completion time, *T16*.
3. Compare *T8* and *T16* to determine how Hadoop scales for Terasort workload.

Elastic Speedup

Elastic Speedup indicates whether adding SUT resources as the workload is running results in a corresponding decrease in the response time— i.e., if we double the resources, we can solve the same problem twice as fast? We initiate a known workload against a given number of servers. As the workload is running, add one or more servers, and observe the impact on performance. A system that offers good elasticity should show a performance improvement when the new servers are added, with a short or non-existent period of disruption while the system is reconfiguring itself to use the new server(s). (Benchmarking Cloud Serving Systems with YCSB, 2010)

ELASTIC SPEEDUP EXAMPLE:

The log files processing workload produces results by processing 100 log files per second. The Company wants the information faster. So while the original 100 nodes are running, they add another 100 more servers to Hadoop cluster.

1. Create a 100-node hadoop workload, and store log files for one year to the HDFS.
2. Start running a log files processing workload.
3. At the end of every hour, copy the new log files created during that hour to the HDFS.

Now, the same log files processing workload is producing results for 200 log files per second.

3.2 Response Time

The ***Response Time*** metric is the same as the traditional response time measurements used by existing SPEC benchmarks. In the client-server context, ***Response Time*** is the interval between when a request is made by a client or workload generator and when the response is received by the client.

A benchmark may also have multiple definitions of Response Time, based on specific scenarios inherent it is domain. For example, a variant ***response time*** definition occurs where the client meters the time taken from when it sends a request to when it receives a response. Web workloads are prime examples. The SPECweb2005 benchmark defines one ***response time*** as the time taken to return the entire page. On the other hand, it defines the ***response time*** for a large download as the time to receive the first byte of the file. The time to receive the entire file is usually measured by another metric, i.e. the throughput.

In each contexts, one determines the ***response time***'s mean value, and various percentiles.

White Box Consideration

In addition to the client-server ***response time*** measurement, ***White Box*** benchmarks have the ability to rely on internally measure response times within a SUT as well as on its external workload generators.

For example, a SOA benchmark tested within a white box environment has direct control of the servers and hosts locations. If the SOA benchmark measures a vendor's underlying SOA platform, then one critical aspect is a set of service clusters located on "separate" machines, as well as on the same machine. Such a benchmark defines service clusters on the SOA platform, and could measure its own response time to a request (after some simulated work), as well as send out its own request downstream to other SOA services.

Black Box Considerations

Black Box benchmarks have no direct knowledge of their servers' physical network connectivity. Various geographic distances may separate the hosts, or all may reside on the same physical hardware within the same data center. The tester cannot not ensure that the subsequent test set retain the same geographic relationships. The benchmark needs to address locality and configuration variation issues.

3.3 Throughput

This metric is the same as the throughput in traditional systems. This refers to the units of work processed by the system or cloud per unit time. The exact definition of this metric depends on the workload, and should be defined in that context. We present the following examples from multiple scenarios, to help guide these definition needs.

Throughput in the context of Hadoop workloads: This is the number of tasks completed per minute when the Hadoop cluster is at 100 percent utilization processing multiple Hadoop jobs

Throughput in the context of Devices: Throughput is the amount of data

read from the device(s) on a single node or cluster expressed in kilobytes per second.

or

written to the device(s) on a single node or cluster expressed in kilobytes per second

EXAMPLES OF NETWORK THROUGHPUT:

Total number of

- packets received per second
- packets transmitted per second
- bytes received per second
- bytes transmitted per second

Throughput in SPEC metrics: SPEC benchmarks Throughput metrics measure the amount of work performed (in benchmark defined units of tasks or operations) per unit of time over the measurement period. A benchmark may include a ramp-up and/or a ramp-down period prior to or after the measurement period. This methodology enables the throughput measurement during a steady state, and/or synchronizes the measurement of parallel operations.

EXAMPLES OF SPEC THROUGHPUT METRICS

Benchmark Metrics	Description
SPEC CPU2006 SPECrate SPECint_rate2006, SPECfp_rate2006	Geometric mean of normalized throughput ratios.
SPECjEnterprise2010 EjOPS	Average number of successful jEnterprise Operations Per Second completed during the Measurement Interval.
SPECjbb2005 bops	Arithmetic mean of Summed throughputs for all the points from N warehouses to 2*N inclusive warehouses

Benchmark Metrics	Description
SPECjbb2005 bops/JVM	Divide the SPECjbb2005 bops metric by the number of JVM instances
"XXX SPECsfs2008_nfs.v3 ops per second with an overall response time of YYY ms"	***XXX*** represents the throughput value obtained from the right-most data point of the throughput divided by benchmark's generated response time curve ***YYY*** represents the overall response time values as collected by the benchmark reporting tools.

3.4 Variability

Variability measures the repeatability of the test results. Many variables affect the repeatability and should be factored into defining the values for this metric. Note that ***variability*** also exists in each of the other metrics defined here. For instance, ***variability*** exists in the collected and computed response times, throughput, provisioning interval, and other metrics.

The ***variability metric*** for any parameter should be based on the standard deviation of the measurement. Variability could be measured against any of the following parameters: *Variability with time* or *Variability with SUT location*. The measured parameter should be collected in a number of iterations and the standard deviation or a metric related to standard deviation should be reported.

White Box SUT

White Box benchmark testers control both the SUT's location and additional processes running on the configuration.

Black Box SUT

Black Box performance metrics are known to show temporal variability due to either changes in actual configurations, or the presence of other background load on the system/systems.

3.5 Durability

Durability is defined as the probability of data loss. Depending upon the context, this entity could be a requirement on the system and not tested in the duration period of a normal benchmark run. Note that each benchmark may specify a different requirement for durability.

3.6 Reliability

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. The reliability of a system is usually measured by the *probability of failures* or by the *mean time between failures* (MTBF).

MTBF is calculated by dividing the total time measured by the total number of failures observed. For example, if 15400 units of SCSI hard drives run for 1000 hours and 11 units fail, then

$$\text{MTBF} = \frac{15400 \text{ x } 1000}{11} = \text{ 1.4 million hours}$$

Note

MTBF is a statistical measure. As such, it cannot predict anything for a single unit. An MTBF of 1.4 million hours doesn't imply that a specific SCCI hard drive will run for 1.4 million hours before failing, only that it is the average of a 15400 sample set.

3.7 Availability

Availability is the degree to which a system or component is operational and accessible when required for use. It is often expressed as a probability (or as a fraction of time) the system is available to service user requests. Example: a telephone system is 99.9999% (or 6-Nines) available.

The time during which the system is not available is called *downtime*; the time during which the system is available is called *uptime*. A small *uptime* and a very small *downtime* combination may result in a high availability measure – which could be misleading. Therefore, the mean *uptime* is also often known as the *Mean Time Between Failures* (MTBF), together with *Mean Time To Repair* (MTTR), and considered as better indicators for availability. Where

$$Availability = \frac{MTBF}{MTBF + MTTR}$$

In fault-tolerant systems, this is a combination of Mean Time Between Failures, Mean Time To Repair.

The exact definition of Availability will be benchmark specific. This metric can be measured, although it may become impractical to obtain accurate readings in the case of highly reliable systems.

EXAMPLES OF AVAILABILITY REQUIREMENTS

Here are some examples of how availability requirements are defined in various contexts/services.

- Classic telephone service examples
  - US telephone service must continue for 80 hours after losing power. During this period, any land line will be able to call another land line telephone subscriber within at least the central office, if not the regional service area.

- US phones must complete a call connection within 10 millisecond or else indicate a busy circuit
- Short message services will usually accept an uploaded SMS within 5 seconds, but do NOT guarantee delivery to recipients outside of their service. Notification of delayed or non-delivery is not required, unlike Internet e-mail messages.

- Most Internet Service Providers guarantee 99.9% availability to their paying e-mail customers, but only 95 to 98% for their non-paying customers.
- Many e-commerce companies run a private "cloud" for their transaction database, to ensure 0% data loss, and 100% transaction integrity.
- Automated teller machines confirm all account debit transactions are complete and accurate before dispensing cash. Loss of access to central servers deactivates affected ATMs.
- DARPA's original specification for the Internet required adaptive techniques to detect and re-route established TCP/IP connections at the network layer (the application layer is a separate matter). This does not apply to the underlying UDP layer. Telephone companies switched to private TCP/IP networks because network equipment makers had better detection and recovery algorithms, once they switched to a digital encoding (aka Ethernet).

3.8 Power

The Power measurement is defined as the total watts used by the SUT during the tests. Guidelines for power measurement are provided in the SPECPower methodology document.

Note that the power metric is another of the metrics that is not applicable or measurable in all cases.

White Box SUT — A ***Hardware/Software Vendor*** or ***Cloud Vendor*** has direct access to the SUT, and can gather power measurements as defined by individual benchmarks.

Black Box SUT — Power measurements may not be possible since the tester does not know the individual "computers" actually correspond to a stand-alone machine or a subset of a larger host. The ***Cloud-Provider*** also may not provide access to power meter measurements, or if one is attached at all.

3.9 Price

We note that while price is an important metric in the context of cloud, this is somewhat temporal, and is clearly a non-engineering metric that may vary from customer to customer. The recommended way to incorporate this aspect is to include the *Bill of Materials* details as part of a benchmark disclosure. This list of model numbers, quantities, software and support information may be used by the benchmark consumer to construct the end price relevant to them. Inclusion of the exact price details in the benchmark disclosure is not recommended.

3.10 Density

Density measures how many instances of the *workload* can be run on the SUT before performance degrades below a specified QOS.

IaaS ***Density*** may refer to the number of virtual machines running on a physical hardware.

PaaS ***Density*** may refer to the number of application servers running on a system.

SaaS ***Density*** may refer to the number of users that the system can service.

White Box SUT The ***Density*** metric is applicable because the tester directly controls how the underlying host management system assigns each server to a physical host.

Black Box SUT The ***Density*** metric is not applicable because the tester does not know if the individual "computers" actually correspond to a stand-alone machine or a subset of a larger host.

4 What Makes a Benchmark a Cloud Benchmark?

A Cloud benchmark will quantify the performance and scalability of cloud computing services. The benchmark's workloads represent the typical set of applications most likely to run in a cloud environment: business infrastructure (i.e. mail, OLTP, automated testing), data analytics, and select "software services" such as database, files.

- A cloud benchmark utilizes both existing standards (SPEC and non-SPEC), as well as adapting others to run within a cloud environment.
- A cloud benchmark's primary and subordinate metrics reflect important considerations such as agility/elasticity, durability, response time, throughput, reliability, density and variability. Other metrics will be documented and included as considerations necessary for comparison, but impractical or too variable to measure. These might include provisioning interval, durability, reliability, power, and price.
- The SUT may run under virtualization conditions or not. It is not considered a requirement. However, the benchmark's description section attempts to standardize the computational capacity available to cloud customers, and facilitate performance comparisons under known conditions.
- Workload generation is benchmark specific, but should be done on a separate set of hardware capable of measuring time reliably and accurately.
- Communication between workload generator and SUT for all the client-server type benchmarks must use TCP/IP or UDP protocol for communication.

- Measurement states correspond to both distinct workloads (simplistic transaction streams) and major subsections identified by the subcommittee as relevant.
- Benchmark scale may be subsumed as part of the workload factors.

In addition to the usual FDR, a cloud benchmark should include the following components:

- Metrics that include ***Elasticity***. The benchmark should be geared to measure ***elasticity*** and ***agility***.
- Benchmark must be capable of running at variable load levels and start and stop on various physical as well as virtual systems.
- Support for Virtualization.

4.1 *Cloudizing* an Existing Benchmark

As pointed in Section Cloud Benchmark Audience Types1.2.2, a cloud benchmark may be used in the context of

1. ***Hardware/Software Vendor*** to ***Cloud-provider*** relationship or
2. ***Cloud-provider*** to ***End-Consumer*** relationship.

Most publicly available benchmarks run to meet the second category.

Given that any workload that runs on a stand-alone system can also run in the cloud, most SPEC workloads are potential candidates to be ***cloudized*** or "*modified to understand a cloud environment*." In this section, we present general guidelines for this step.

Characterize Workload Types

SPEC benchmark workloads fall into two types:

Throughput	Designed to run at different rates with scaling.
Batch jobs	Designed to record completion time.

Most workloads that run on regular computer systems can also run on the cloud. Given this, the existing benchmarks that address various workload areas may intend to "***cloudize***" their workloads. The following requirements are to be put in place in order to make sure that the resultant benchmark is cloud-specific.

Separate Locations

SPEC benchmarks do not account for SUTs physically located in other sites. The benchmark should run from client systems, physically separated from the SUT, accessing the SUT via a campus or wide area network. The client systems should be reliable, so the benchmark can make time related measurements. (reference to *Run Rules* of various benchmarks)

The SUT defined for the workload must be accessible via network connections.

Add Cloud-specific Metrics

Where relevant, the benchmark should consider adding cloud-relevant metrics including ***Elasticity*** and ***Agility***.

Most cloud computing instances allow multiple applications to share computing resources on a single computer. This means the tester may or may not control all applications sharing the SUT during a benchmark run.

White Box

A Hardware/Software Vendor or Cloud Vendor knows and controls what other applications run on the SUT.

Black Box

The End-Consumer does not know or Cloud Vendor chooses to randomly select machines from the computing cloud. The tester does not know the full application set sharing the SUT. The benchmark should measure temporal variability in its metrics. This can be done by running the benchmark at different times of the day to different times that may be appropriate to measure and characterize the variability in performance.

Include Scalable Workloads

The benchmark harness should provide a dynamic load. In the case of batch jobs, this could mean the ability to add, and configure or delete instances of the test systems. In the case of throughput oriented workloads, this could refer to an ability to vary the size of the workload as well as start and stop new instances.

4.2 *Cloudize* Existing SPEC Benchmarks

The Working Group asked each subcommittee chairperson some questions about existing workloads and methodology. The following assessments and suggestions are based on their responses or a review of sample disclosures.

Guidelines for SPEC Benchmarks

In the table below, we provide some guidelines on the existing SPEC benchmarks, whose workloads are likely candidates to be extended into the cloud space.

Factors & Actions	Workload Type	Scalable Harness?	Scalable Workload?	Introduce Scaling?	Define a Cloud SUT?	Cloudize Benchmark Metric	Add Metric: Elasticity	Add Metric: Variability	Add Metric: Provisioning Interval
CPU	B	N/A	N/A		N				

JBB 2005	T	×	×	×	×	×	×	×	×
JBB 2012	T	×	×		×	×	×	×	×
JEnterprise	T	×	×		×	×	×	×	×
File Server	T	×	×			×	×	×	×
Mail 2001	T	×	×		×		×	×	×
Mail 2009	T		×	×			×	×	×
Power	?								
SIP	T								
SOA	?								
Web	T		×	×	×	×	×	×	×
Virtualization	T	×	×		×				

Benchmark Changes

These are the currently known high-level modifications to each benchmark:

OSG Benchmark	Additional Notes
Web	Eliminate manual setup steps
Mail	Reactivate harness scaling code in Mail2009 harness
CPU	▪ Benchmark needs to run only on a single system ▪ Use a subset of CPU workloads to compare the actual machine provided in cloud contexts vs. native lab systems.
Virt	TBD
JBB2005	TBD
JEnterprise	▪ Modify Application servers to suit purpose of elasticity ▪ Make harness automatic
Power	N/A
SIP	• Make harness and workload generators scalable • Include Cloud metrics

4.3 Dos and Don'ts of Benchmarking a Cloud

Here is a list of Do's and Don'ts to note while creating a cloud benchmark.

Do's

- Consider the variation in performance due to the background load on the SUT.
- Treat virtualization as a technology behind the cloud and transparent to any cloud benchmark. But virtualization should not be a requirement.
- Vary the intensity of the workload over time, and both up and down in different cycles) to measure the elasticity.

Don'ts

- Report any metric that requires pricing. Instead provide all necessary metrics for the consumer to compute the total cost (same as other benchmarks?)
- Report a metric that is not observable to the consumer. (Same as other benchmarks?)
- Include any time spent outside the boundary of the SUT (for example in the Internet) for any latency type metrics. (Same as other benchmarks). However when testing a ***Black Box***, this will be impossible since the SUT in the cloud is external to the tester's benchmark harness and workload generators. Assume the tester has no visibility into the cloud's physical infrastructure.

5 Tools to Measure Cloud Metrics

The OSGCloud team investigated various tools and frameworks that purportedly tested and measured cloud computing. The following are only some of the tools found in open source or restricted release forms. The team also hopes to have canned demonstrations available for viewing.

5.1 AEOLUS (Red Hat)

Aeolus is an Open source project sponsored by Red Hat, designed as framework to create and manage an on-premise hybrid cloud *Infrastructure-as-a-Service* (***IaaS***). It provides self-service computing resources to users in a managed, governed, and secure way. You can deploy and manage applications on any type of server - physical, virtual, and public cloud.

Aeolus is focused on two distinct sets of capabilities related to ***IaaS***:

1. Provide the tools to build and manage hybrid clouds
2. Provide the tools and processes to build, manage and launch applications that run on hybrid clouds

It integrates with existing products and technologies, including physical servers and virtualization platforms from other vendors, to provide the easiest on-ramp to an

on-premise cloud. Using Aeolus, you can migrate to multiple public cloud providers, including those running a software stack from a different vendor.

Aeolus delivers automated resource management, automated workflow and policies to manage a diverse set of business applications in hybrid cloud environments. It also allows organizations to leverage public clouds for pay-as-you-go utility computing without creating another silo or losing control of IT security or governance.

You can manage applications and infrastructure together as one unit, rather than as separate silos, simplifying the task of ensuring continuous compliance. Thus, all the infrastructure and applications will stay in sync with established policies at all times.

AEOLUS Website http://aeolusproject.org

5.2 BITT (Intel)

Intel® Benchmark Install and Test Tool (Intel® BITT) provides tools to install, configure, run, and analyze benchmark programs on small test clusters. It is implemented in *python* and uses *gnuplot* to generate performance plots. **Intel® BITT** currently runs on Linux and been used on OracleVM, Amazon and various hardware platforms.

These are the major tools found in **Intel® BITT**:

Intel® BITT Component	Function/Role
installCli	installs tar files on a cluster
monCli	monitor performance of the cluster nodes and provides options to start monitoring, stop monitoring and generate cpu, disk i/o, memory and network performance plots for the nodes and cluster.
hadoopCli	automates the set up and control of the Hadoop test environment
Command scripts	enable configurable scripts to control monitoring actions.
XML files	Sets benchmark configuration properties, including location of installation, monitoring directories, monitoring sampling duration, the list of the cluster nodes, and the list of the tar files that need to be installed.
Templates	Allows configurable plot generation

BITT Website http://software.intel.com/en-us/articles/intel-benchmark-install-and-test-tool-intel-bitt-tools/

5.3 CloudBench (IBM)

IBM's **CloudBench** (CB) is a meta-benchmark framework designed for *Infrastructure-as-a-Service* (***IaaS***) clouds. It automates the execution, provisioning, data collection, management and other steps within an arbitrary number and types of individual benchmarks. CB will do the following:

- Exercise the provisioned VM's by submitting requests to applications (individual benchmarks) that run on the provisioned VMs.
- Exercise the operational infrastructure by submitting VM provision/de-provision requests to the Cloud management platform.
- Supports Black Box testing, with some support to embed data collection nodes inside the SUT to collect metrics usually associated with White Box tests.
- Manages multiple application sets. The default workload generates various types of workloads, but can be extended to support local custom application sets.
- Measures elasticity components: provisioning time, scaleup, as well as variability, agility

CloudBench Website Currently, not publically available. However once benchmarking activity begins, it can be released or licensed. Please see Appendix C for a detailed description of the tool.

6 OSG Cloud Subcommittee

An OSG Cloud subcommittee should be formed to both release Cloud Computing benchmarks, and work with other SPEC subcommittees when they are ready to update their benchmarks into Cloud Computing environments.

6.1 Cloud Subcommittee Charter

We propose starting a subcommittee with the following charter:

- Establish a common definition and methodology to measure cloud performance
  - Some of this exists in the work done by the working group, but we can continue refining this
- Framework for the Cloud Benchmark
  - White box
  - Black box
- Develop benchmarks using representative cloud workloads not covered by other OSG groups.
- Work with other SPEC sub-committees to add cloud metrics to their benchmarks.

6.2 Subcommittee specific Issues

We have identified the following topics the Cloud subcommittee needs to address.

- Provide an API layer for benchmarks to make a single consistent call to Cloud-Providers.
- How to spin up and down? Not coordinating may lead to harmonic oscillations.
- Are there simpler things we could do?
- May want to start a new instance, but not load it.
- Which of the characteristics can be addressed with the current benchmarks during the next iteration period of the benchmark?

Appendix A. OSG Cloud Contributors

The following people in OSGcloud working group actively contributed to this report.

Dean Chandler and Nurcan Coskun (Intel)

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Nicholas Wakou, Indrani Paul, and Louis Barton (Dell)

Mark Wagner (Red Hat)

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KIT

Yun-seng Chao (Supporting Contributor)

Appendix B. Cloud Computing Use Cases

This section elaborates on the Computing Use Cases in Section 1.3.1.

Social Networking

A typical configuration probably has the following components and behavior:

- Recommendation engine
- Advertisement servers
- Search engine(s)
- Chat servers
- Conferencing servers
- Ratings engines and data sets
- Large quantities of data reads and writes of small or moderate size
- One or more Memory Cloud(s)
- Access to one or more Digital Rights Management services
- User Management and Verification
- Payment servers (Credit cards, electronic transfers)

Collaboration

A typical configuration probably has the following components and behavior:

- Search engine(s)
- Chat servers
- Conferencing servers
- Large quantities of data reads and writes of small or moderate size
- One or more Memory Cloud(s)
- User Management and Verification

Publicly accessible collaboration services might also use

- Recommendation engine
- Advertisement servers
- Ratings engines and data sets
- Payment servers (Credit cards, electronic transfers)

Mail / Messaging

A typical commercial configuration probably has the following components and behavior:

- Run e-mail servers (Exchange, sendmail, open source mail servers)
- Anti-abuse/mal-ware processing engines (filters SMTP, SMS, IM, etc)

- IMAP4 servers (long-lived connections, some compute intensive commands)
- Large quantities of data reads and writes of varying sizes
- User Management and Verification

More sophisticated or free services might also use

- Coordination with calendar servers
- Advertisement servers
- Search engine(s)

Data Analytics

This wide category of computing include

- Expertise Searches for enhanced search results, and generated by
  - Editors and authors who generate useful meta-data
  - Users who generate click-streams and other data
- Artificial Intelligence
  - The Ranking problem
  - Supervised machine learning
  - Iteratively retrieve and rank documents or information quanta
  - Incorporate all available cues: text similarity, classifications, citations, user behavior and query logs
- Process large data sets (Big Data, user profiling, pattern processing)
  - Extract from logs, transform and load processes
  - Cluster similar queries together
  - Extract, normalize, collate citation contexts
  - Needle in the hay stack searches (SETI)
- Clustering
  - Process N-dimensional data sets to find natural partition clusters, similar items within and between clusters
  - Find customer segmentation boundaries or company strategies
  - Find groups with similar behavior
  - Find customers with unusual behavior
  - Search large database of CAD drawings, groups of similar parts, identify standard parts with each group, and use these standard parts instead of custom parts

Data Warehousing / Mining

This computing category builds on large sets of both structured and unstructured data.

- Data collection
- Data preparation (data factory) – ETL (extract, transform, load) reports

- Business intelligence analysis
- Ad-hoc queries

NoSQL Databases

These non-relational databases can support peta-byte scale data sets, distributed across hundreds to thousands of machines. They are used where '*weak consistency guarantee*' policies suffice. Real-time web applications, document databases, graph databases, key-value data stores are among some current applications of this technology.

Business OLTP

This long-standing processing type is characterized by high data I/O volumes and well defined data sets. Both real-time and scheduled processing exist.

Memory Cloud

A group of machines maintain a coherent and shared data space used by

- Web search databases and queries
- Graphs of social network connections
- Virtualized Java VMs – multiple Java applications share the same memory space
- Web productivity suites
- Leverages NoSQL or key-value pair databases

HPC

High Performance Computing

- Monte-Carlo simulations
- Biological Molecule simulations
- DNA sequence analysis
- Computational fluid dynamics
- Weather and climate simulation
- Fraud detection

On-line Gaming

Similar to social networking or collaboration, but also maintain time-sensitive services

- Game servers
- Session servers
- Game databases
- Player databases of relationships, roles, characters
- User Management and Verification
- Advertisement servers

- Recommendation engine
- Payment servers (Credit cards, electronic transfers)
- Large quantities of data reads and writes of varying sizes

Streaming Audio/Video

An increasing number of consumers access music, books, or videos from various media distribution companies.

- Recommendation engine
- User Management and Verification
- Media retrieval
- Media format conversions
- Advertisement servers
- Payment servers (Credit cards, electronic transfers)
- Access to one or more Digital Rights Management services
- Large quantities of data reads in fixed sized blocks
- Less quantities (but still numerous) uploads and data writes in fixed sized blocks
- Time-sensitive I/O to users

Voice over IP

Replacing and expanding audio communications.

- Network connections limit determines host count, not cpu, for audio conversations or conferences.
- CPU and network connection limits determine host count for video conference or personal calls.
- Media format conversion servers
- User Management and Verification
- Bi-directional audio streams of varying sizes
- Time sensitive I/O to and from users
- Payment servers (Credit cards, electronic transfers)
- Usually accompanied by Instant Messaging / Chat

Appendix C. CloudBench Description

Introduction

CloudBench (CB) is framework that allows automated execution of meta-benchmarks on multiple "Infrastructure as a Service" (IaaS) Clouds. In the context of CB, a meta-benchmark is a composition of an arbitrary number and types of individual benchmarks, arranged with the purpose of exercising both the Cloud's provisioned VMs and Cloud's operational infrastructure. Regarding the first Cloud characteristic, the exercising is achieved by the submission of requests to applications (individual benchmarks) that runs on the provisioned VMs. For the second, it is achieved by the submitting of VM provision/de-provision requests to the Cloud management platform (which will in turn direct it to an hypervisor). While the data collection on the performance of benchmarks running on individual VMs on a Cloud is an intrinsic characteristics of any IaaS Cloud (i.e., a "black box" view of Cloud performance is the standard view for public Clouds), collection on some of the specific characteristics of resource usage by a group of VMs on an hypervisor (i.e., a "white box" view) requires special provisions from the Cloud, to allow direct access to the hypervisors. While CB can certainly collect and process both black-box and white-box data, the second type is usually only made available on private Clouds. Still is important to note that even though unable to collect detailed hypervisor resource usage information from public Clouds (e.g., Amazon EC2, Rackspace Cloud Servers), CB can and will collect information pertaining the time to provision a new VM, even in a public Cloud.

The "application performance" capabilities of a Cloud are assessed by determining what is the maximum combined performance achieved by the benchmark set being executed on Virtual Machines (VMs) provisioned on a Cloud This particular set of metrics is of interest primarily for Cloud users or "consumers". These could, by designing an experiment to match the characteristics of both their own set of internal applications and its access patterns (i.e., application load levels and load variation), have a projection on how adequate, performance-wise or even better price-performance-wise, a particular Cloud would be. This manner, before deciding to move its internal applications to a Cloud, a consumer can assess multiple Cloud providers in a manner that is not only objective and consistent, but also fully automated.

The "operational performance"[2] capabilities are relevant first and foremost for Cloud providers. In addition to a particular set of selected benchmarks, a meta-benchmark execution can also include a description of one or more patterns for the arrival and departure of VMs. This manner, the natural flow of new consumers being added to the Cloud (through VM provisioning), and old consumers leaving it (through VM de-provisioning) can be replicated. By combining this continuous motion with the constant benchmark execution on individual VMs, a provider can assess the capabilities of its own infrastructure to quickly incorporate new users while in the face of constant (and eventually, heavy) computing resource use by old users.

From the users perspective, CloudBench can be seen as an "execution engine" for the meta-benchmark scenarios composed by them. The scenarios are assembled by the employment of several abstractions built by CB for this purpose. The first relevant abstraction is designated "Application Instance" (AI). An AI is a set of VMs, logically grouped together in order to execute a specific benchmark. For instance, the "DayTrader" application benchmark, built to simulate a complete online stock trading system (users can login, view their portfolio, lookup stock quotes, and buy or sell stock) is composed by at least three VMs: one executing an automated "load driver" (to simulate users actions), one executing the application server for user action processing (e.g., WebSphere Application Server) and finally one VM executing a database server for results persistency (e.g., DB2). Another relevant example of an AI is the Hadoop application. It is composed by one "master" VM running control processes (e.g., JobTracker, NameNode) and one or more "slave" VMs, running information operation processes (e.g., DataNode, TaskTracker). It is important to note that the concept of an AI is internal to CB. While a Cloud management platform is required to keep track of the state of individual VMs that it provisions, typically there is no information on the dependence and/or association among these. In addition to the actual composition of an AI, CB allows the experimenter to specify a description of the variation of the "load intensity" level to be applied to an AI, in the form of random distributions. It is important to note that actual meaning of the "load intensity" level is entirely AI-specific. For instance, while "level" might refer to the number of simultaneous clients in case of a DayTrader AI, it might refer to the size of the dataset to be "mapped and reduced" in case of a Hadoop AI.

[2] From CB's standpoint, "operations" are VM provisioning/de-provisioning, VM "image capture" and VM migration (the latter two are not yet fully included on the CB).

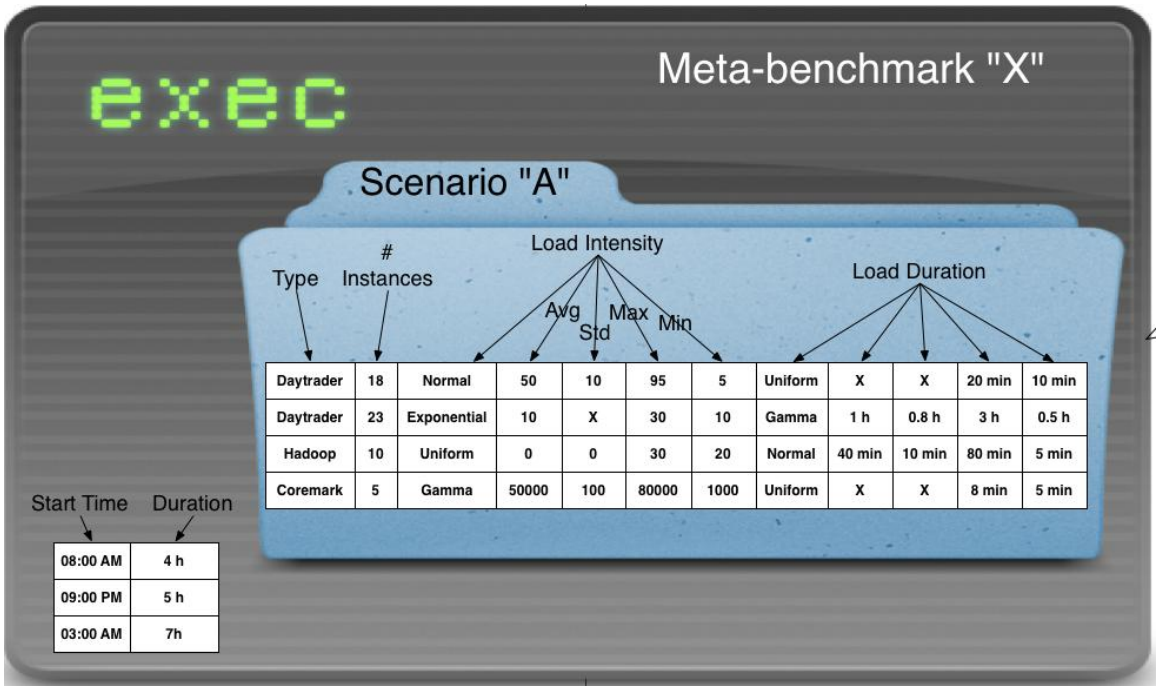

Figure 1 – Application performance assessment experiment description

The AI is the primary abstraction used to describe scenarios where the application performance capabilities of a Cloud are assessed. A scenario is composed by a collection of AI groups (called simply "scenario" in the CB nomenclature). By adding an execution "time table" for such scenario, a meta-benchmark run is defined. The Figure 1 illustrates it with an example.

A scenario is composed by the specification of multiple AI groups, each with its own load variation characteristics. The variation is expressed by two random distributions, one used by CB for the determination of a specific load intensisty level, and another used for the determination of the duration of a given intensity level. The random distribution is specified by five parameters: distribution type (e.g., normal, exponential, gamma, uniform, etc.), average, standard deviation, maximum and minimum values. For each individual AI in a group, CB applies a different "load intensity" level lasting for a specific "load duration" time. At the end the "load duration" time, new values for both load intensity and load variation are selected from the random distributions. Every individual AI within a group has individual load values selected for it. AIs on a group share the same random distributions, but not the same values. As can be seem in the example, an experimenter can even specify different AI groups with the same benchmark types, but with different load variation parameters.

The second relevant abstraction introduced by CloudBench is the "Application Submitter" (AS). An AS is a process that continuously creates and destroys AIs on a Cloud, simulating the behavior of cloud consumers arriving and leaving. To this end, the AS create new AIs at specific intervals, and assigns a lifetime to each individual AI, periodically destroying those that are being executed for a time longer than its expiration. This abstraction is of primary interest for Cloud providers, as it allows the specification of scenarios with multiple Application Submitters are used to produce consumer population fluctuation while keeping the Cloud resource usage at a desired level. The Figure 2 illustrates a complete experiment for the assessment of the management (provision/de-provision) capabilities of a Cloud.

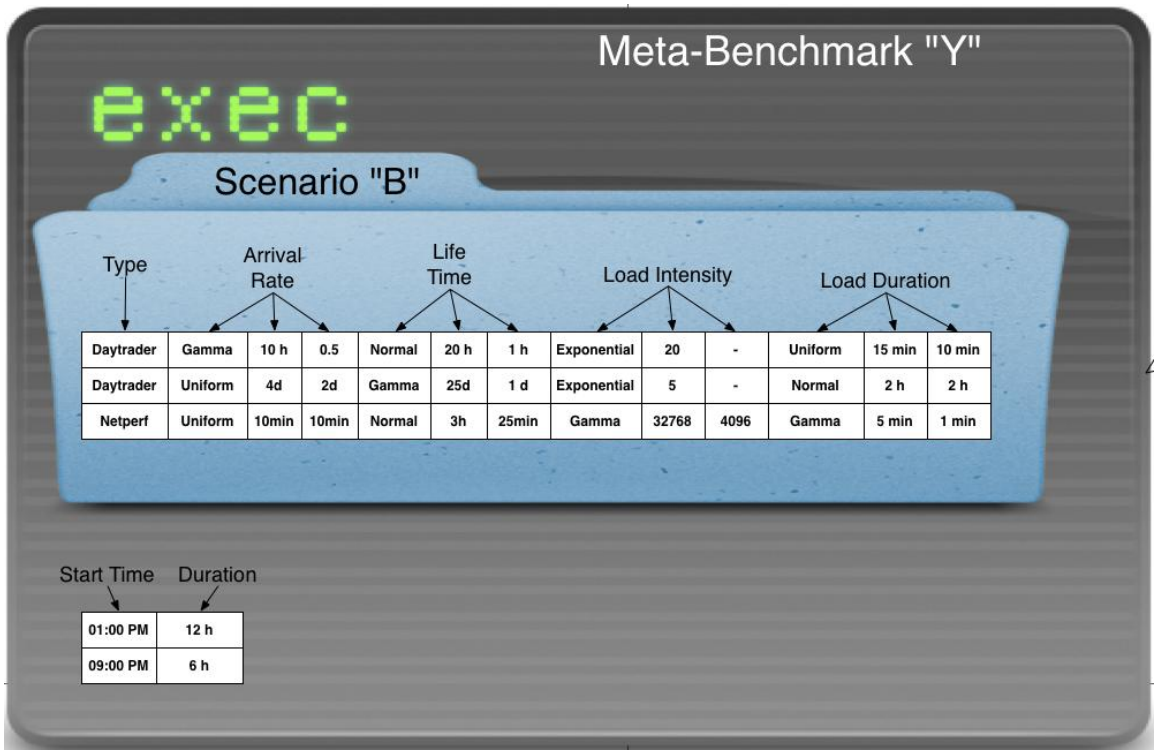

Figure 2– Runtime performance assessment experiment description

In this case, a scenario is composed by the specification of multiple AS groups, each with its own arrival rate, lifetime and load variation characteristics. Exactly as it is the case for the AIs, the all characteristics here are expressed by random distributions. In the case of arrival rate, a new value is selected from the random distribution after every individual AI creation. Each individual AI within an AS also is assigned its own individual lifetime value. Finally, the load variation characteristics are also

selected from the appropriate random distributions and applied to individual AIs within an AS. AIs generated by an AS share random distributions, but not particular values for any of its parameters. For illustrative purposes, the values of maximum and minimum for each distribution were omitted in the description of the second experiment, but they are exactly the same (i.e., average, standard deviation, maximum and minimum) enumerated during the description of runtime performance assessment experiments.

It is important to note that the use of random distributions, while highly desirable due to its capability of capturing the behavior of real Clouds through modeling, does not give any predictability in terms of monotonicity on the specified characteristics of an AI or an AS. For instance, using a random distribution for load intensity level provides no guarantees that a particular AI will experience constantly growing intensity. In case predictable growth or shrinkage of load is more important than random variation, any AI or AS characteristic can be also specified as a arithmetic or geometric progression, assuring monotonic variation on such characteristic.

Once designed, a scenario has to be translated to CloudBench's meta-benchmark language description. This language is based on two primitive directives – "attach" and "detach" – that represents the activation or de-activation of actual objects (e.g., VMs, through the "vmattach" and "vmdetach" directives) or CB abstractions (e.g., "aiattach", "asdetach") during the meta-benchmark's lifecycle. This language is processed by a frontend, which runs a Command Line Interface (CLI) that allow CB users to interactively follows the progress of a meta-benchmark. An execution trace is normally stored on text file containing a sequence of directives. The use of text files allows quick re-execution if necessary, even in an automated fashion. Illustrative examples for the experiments displayed on Figure 1 and Figure 2 follows:

Experiment 1

```
cldattach ec2 AMAZ /*attaches a new Cloud called "AMAZ" using the EC2 API*/
vmcattach AMAZ us-east-1 /* All VMs will be created on EC2's "us-east-1"
aiattach AMAZ daytrader normal,50,10,95,5 uniform,X,X,20min,10min
/* this command is repeated 18 times, since we want do define the instances
individually */
aiattach AMAZ daytrader exponential,10,X,30,10 gamma,1h,0.8h,3h,0.5h
/* repeat 23 times */
aiattach AMAZ hadoop uniform,X,X,30,20 normal,40min,10min,80min,5min
/* repeat 10 times */
aiattach AMAZ coremark gamma,50000,100,80000,1000 uniform,X,X,8min,5min
/* repeat 5 times */
```

```
waitfor 4h /* the experiment start at 08:00AM*/
ailist AMAZ
statealter AMAZ ai_all "suspend" /* stop load execution on all AIs */
waitfor 9h /* the next execution is 9:00 PM*/
statealter AMAZ ai_all "active" /* resume load execution on all AIs */
wait for 5h
statealter AMAZ ai_all "suspend" /* stop load execution on all AIs */
waitfor for 1h /* the next execution is 3:00 AM*/
statealter AMAZ ai_all "active" /* resume load execution on all AIs */
waitfor 7h
aidetach AMAZ all
vmcdetach all
clddetach all /* ends the meta-benchmark, cleans up any state*/
```

Experiment 2

```
cldattach ec2 AMAZ
vmcattach AMAZ us-east-1
asattach AMAZ daytrader gamma,10h,0.5,12h,2h normal,20h,1h,36h,4h
exponential,20,X,40,10 uniform X,X,15min,10min
asattach AMAZ daytrader uniform,X,X,4d,2d gamma,25d,1d,40d,5d
exponential,5,X,10,1 normal,2h,2h,10h,1h
asattach AMAZ netperf uniform X,X,10min,10min normal,3h,25min,6h,10min
gamma,32768,4096,10000,1000 gamma,5min,1min,10min,1min
waitfor 12h /* the experiment start at 08:00AM*/
asdetach AMAZ all
waitfor 20h /* the next execution is 9:00 PM*/
asattach AMAZ daytrader gamma,10h,0.5,12h,2h normal,20h,1h,36h,4h
exponential,20,X,40,10 uniform X,X,15min,10min
asattach AMAZ daytrader uniform,X,X,4d,2d gamma,25d,1d,40d,5d
exponential,5,X,10,1 normal,2h,2h,10h,1h
asattach AMAZ netperf uniform X,X,10min,10min normal,3h,25min,6h,10min
gamma,32768,4096,10000,1000 gamma,5min,1min,10min,1min
waitfor 6h
aasdetach AMAZ all
vmcdetach all
clddetach all /* ends the meta-benchmark, cleans up any state*/
```

The set of produced meta-benchmark directives is then translated to Cloud-specific commands (to have the appropriate VMs to be provisioned) and individual benchmark-specific commands (e.g., start a database on a given VM), being then submitted to a Cloud. The main purpose of the CB is to automate the meta-benchmark execution, including the metrics collection, allowing even for simultaneous execution on multiple Clouds. One important aspect to be clarified is regarding the expansion on the scale of individual AIs. CB can certainly increase load on an individual AI (all it is needed is the change on the load variation characteristics on this AI, for instance, increasing the average of the random distribution) or increase the total load on a Cloud by increasing the number of AIs. It does

not have the ability, however, to increase the number of VMs (i.e., the "size") of an individual AI. The "scale-out" of an AI is an operation that is very application-benchmark specific, and therefore has no directly mapped uniform directive on CloudBench. For instance, while "scale-out" is an almost trivial operation for a Hadoop-type AI (all that is needed is the increase in the number of "slave VMs") it would require significant configuration changes for a DayTrader-type AI (e.g., clustering, load-balance configuration changes). The Figure 3 displays the usual execution flow for CB.

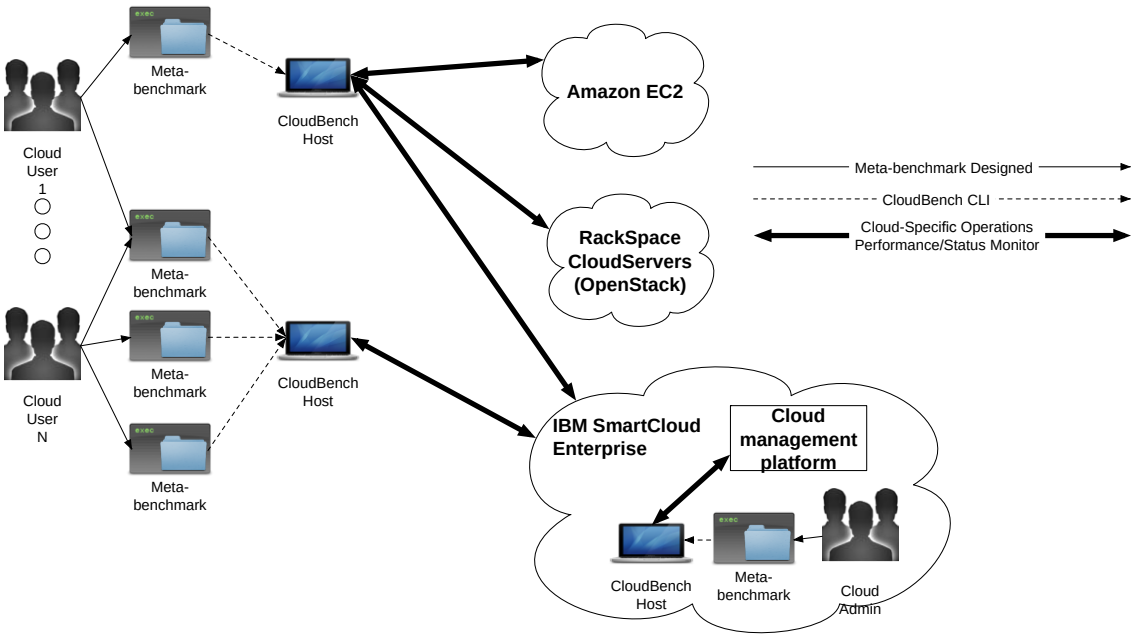

Figure 3 – CloudBench's meta-benchmark execution flow.

While the Cloud maintains the state of provisioned VMs, the state of each AI and AS has to be maintained by CB itself. To this end, CloudBench manages its own Object Store (OS), which contains all the relevant information pertaining an experiment's execution lifecycle. Information about each created AS and AI, the AI's lifetimes, the random distributions associated to each AI and AS, the list of VMs that needs to be provisioned by a new AI of a given type, are all registered on the OS. Being an entity completely separated from the CloudBench frontend CLI, the OS allows asynchronous changes to an experiment to be submitted from multiple sources (i.e., multiple CLIs can connect to the same OS), to dynamically and adaptively change an experiment during its execution. The OS is

implemented as an in-memory key-value store (in the current implementation, Redis is used, but other stores, as Memcached or Voldemort would be equally suitable). This particular form of implementation for the OS was selected by its scalability (key-value stores can be easily and quickly horizontally scaled), its high write performance (10s of thousands of inserts per seconds even on desktop computers) and its ease to initial setup. It is important to note that the use of an in-memory store is possible mostly because there is no need for persistency on this data. While the state of each AI and AS is important during the experiment's execution, it does not need to be kept after it finishes.

Given the fact that CB is also in charge of performance data collection, a second data store, designated Metric Store (MS) is also managed in the same way of the OS. The details of the performance metrics collection will be made explicit on the next section, but for now suffices to say that the requirements for it, specially in terms of write performance are even more stringent than the ones required by the OS. For this reason, the MS is also implemented as an in-memory key-value store. Contrary to the OS however, the MS do needs persistence of the information stored there, since such information is the main outcome of an experiment executed by CloudBench. This requirement is fulfilled by the existence of one or more "performance reporters", processes that reads data from the MS and writes it to individual comma separated values (csv) files for latter analysis and processing. This manner, the performance data can be submitted to MS is a manner that is both scalable and flexible, while this same data can be stored asynchronously.

As can be seen in the Figure 4, CloudBench's architecture is inherently distributed. The creation of a new AI triggers the spawning of a short-lived "application instance creator" process on the CloudBench host (the same machine that executes the frontend CLI), which will be in charge of the VM creation and automatic application startup. After that, however, each AI has a VM selected as a "driver", which will act as a manager to this AI, selecting load intensity levels and load duration through the "Load Manager" (LM) process and collecting performance data through the "Performance Collector" process. Both processes will run on the "driver" VM throughout the AI's entire lifecycle. In addition to that, each AS has a long running "application submitter daemon" associated to it. This daemon is kept running on the CloudBench host, continuously creating new AIs at selected intervals (the inter-AI arrival time) and destroying "expired" ones.

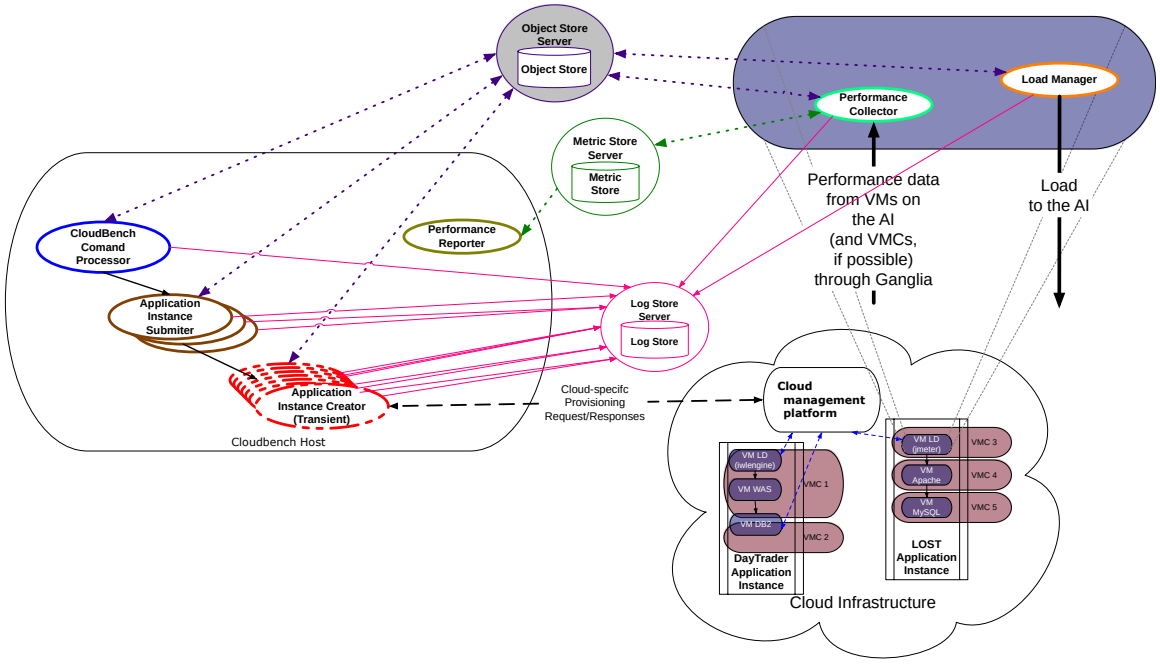

Figure 4 – CloudBench's multi-process architecture description.

How does CloudBench collect performance data?

The two different aspects of Cloud performance explored by CloudBench have very distinct collection mechanisms. For the operational performance, the relevant performance data pieces are simply the time intervals between two successive events. During the provisioning of a new VM, CB will record the time between the VM creation request and the actual VM start, the time between the VM start and VM establishment of the VM's network connectivity and finally the time to start an individual component application on a VM (e.g., time to start a database or web server on a given VM). All these metrics, being fixed during the VM's lifecycle (they happen only once) are in fact stored by CB on the Object Store, instead of the Metric Store. Nevertheless, they are also read by the same performance reporter previously described and also stored on a (separate) csv file.

The performance metrics collection for the application performance is somewhat more elaborated. As previously explained, each individual AI has a VM elected as its "driver" (co-located on the Cloud with the other VMs on an AI). This VM will run a "Performance Collector" process, which will receive performance data from all VMs belonging to this same AI. This data is then processed (only the data format is changed) and is written,

without any summarization, on the MS. Asynchronously, the performance reporter reads the data from it and writes it to a csv file.

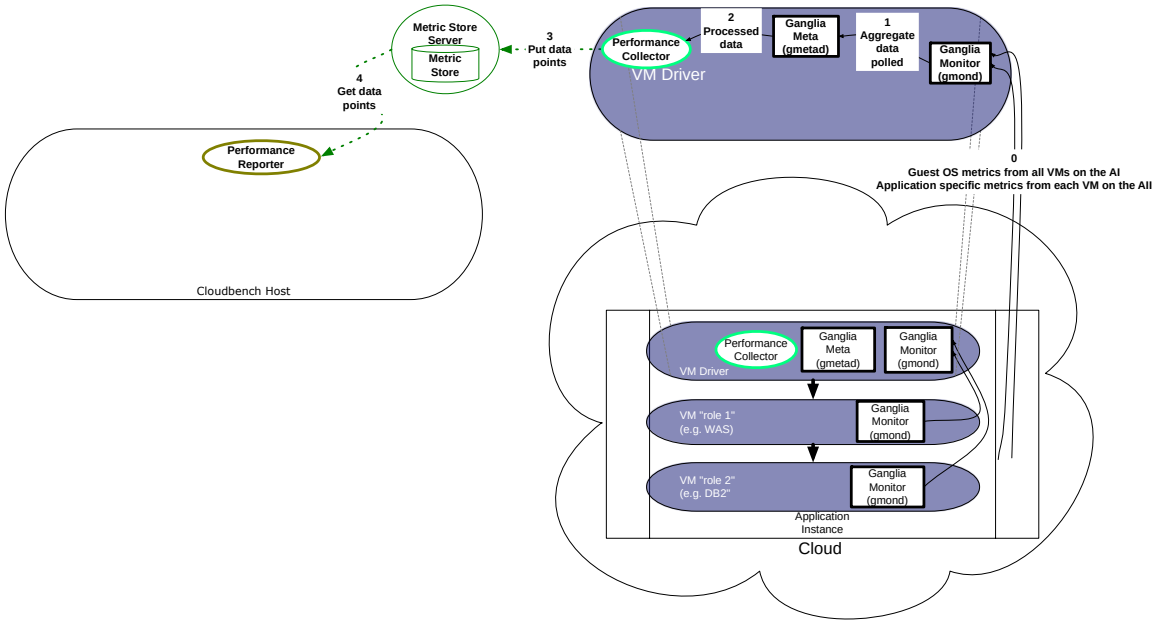

Figure 5 – Runtime performance data collection flow.

The runtime metrics collection requires two components: collectors and a transport framework. Although these components are theoretically orthogonal, in practice there is great synergy in the leverage of an integrated solution. In the case of CloudBench, the Ganglia framework is used. Ganglia's architecture has two types of processes: a ganglia monitor (gmond) that can trigger the collection an then the sending of the performance data and ganglia meta daemon (gmetad) which aggregates data from multiple gmond processes (running on multiple VMs). The performance information is exchanged through an XML data representation, transported (typically) over UDP. Ganglia has native collectors for VM Operating System metrics, like CPU, Memory, Network and Disk I/O (the data collected is very similar to what would be obtained by utilities like ps, mem, sar, netstat and iostat). In addition to that, a special utility (called "gmetric") is provided to allow any arbitrary value to be inserted on the same transport data stream used be the native collectors. In case of CloudBench, this utility is used to report application-specific metrics (e.g., Application servers Performance Management Infrastructure queries or SQL queries to a database) back to the VM in

charge of concentrating all data. The Figure 5 presents the runtime performance data collection flow.

The "Performance Collector" continuously reads (in fact, pulls) performance data from the gmetad concentrator (both running on the "driver" VM) and writes it to the Metric Store. While Ganglia is used here mainly for its ease of use and maturity, there is nothing unique to it that prevents other frameworks from being employed with the same effect. Frameworks like OpenTSDB or Collectd could be used in the very same way that Ganglia is. From the CloudBench perspective, all that is required is the delivery of performance metrics to a "driver" VM, where they could be properly read by the "Performance Collector" process and written to the MS.

How does CloudBench incorporate new benchmarks and workloads?

During an AI creation, CloudBench obtains a list of VMs with specific "roles", being each "role" associated with a set of actions to be automatically performed. For instance, a VM with a "role" DB2 requires a database instance of this type to be automatically started there. Therefore a script that executes the startup of this application has to be provided for CloudBench. While CB will automatically transfer the script to the appropriate VM, execute it, react appropriately according to the execution results (e.g., re-trying if the script signals failure), the actual script is highly application (and even VM Operating System) dependent, and has to be provided by the owner of the benchmark being added. A similar case is to be made for the actual benchmark process. A new benchmark also requires an appropriate execution script that can then be automatically executed by CloudBench. Typically, such script should take as parameters the load intensity and the load duration. This second is optional, since CloudBench can be programmatically instructed to unconditionally kill a benchmark process instance with a given load level before starting a new one.

The requirements for a new benchmark can be summarized as follows: for each VM application that composes an AI, supply a start/re-start script, and supply also a benchmark execution script.

CloudBench Instantiation on Amazon EC2

In order to deploy CB on a public Cloud like Amazon EC2, it is highly recommended that all CloudBench architectural components are co-located within the same Cloud. This manner the CB Host, housing the CLI processor, the AS daemons (and the associated short-lived AI creation processes) and performance reporter process, can have direct network

access to the VMs belonging to the newly created AIs. This access is of importance during the creation of new AIs: the "application instance creator" process requires a very brief SSH access to the AI's VMs at the beginning of its lifecycle, in order to startup every application component of a given benchmark before actual load can be applied to it.

Given the fact that each individual AI's "driver VM" requires constant access to both the Object and Metric Stores throughout its whole lifecycle (for the performing of "load management" and performance collection activities), there is a clear benefit for CB's function in the placement of such components in close proximity with the AIs, with the lowest possible network access latency.

Collocating all three CB components on a single VM on the same public Cloud has two additional advantages, in addition to remote connection performance. The first is the ease of deployment, since there is no need for security configuration changes on the local network (as there would be in the case CB components are not co-located in the same Cloud) to allow the VMs to reach the Object Store and Metric Store (again, with a much higher latency anyway). The second advantage is on the potential cost savings. While public Clouds normally charge for data traffic that crosses the boundary of its premises, they do not have the same restriction for traffic between co-located VMs.

The CloudBench code is fairly self-contained – a single directory contains all python modules required for its operation – with a few third-party python modules that could also be easily installed on a newly instantiated VM on EC2. In addition to that, the fact that both the Object Store and Metric Store use the same key-value store (Redis) makes the deployment of these on a newly created VM fairly simple. Alternatively there is always the possibility of the use of an already configured "CloudBench template VM", available on EC2.

Metrics

The mapping between each specific metric collected by CloudBench during the execution of a meta-benchmark and its role in the assessment of specific Cloud characteristics is the following:

Throughput: Used in the assessment of "application performance" characteristic of a Cloud, this metric is sent, by the supplied "execution script", after every execution of an individual benchmark on an AI (an "execution" represents the running of an individual benchmark with a given load intensity level, for a given load level duration)

Response Time: Very similar to Throughput.

Elasticity: Used in the assessment of "operational performance" characteristic of a Cloud, this metric is collected by the CloudBench Host, during the creation of a new AI. The time to create a new AI is broken down in specific sub-components, like the time between the VMs' creation request and the VM's starting, and the time to have the applications on the VM started.

Agility: Also used in the assessment of "operational performance". Given the fact that CB does not have provisions to increase the "size" of AI (i.e., the number of VMs that composes an AI) automatically, the only metric collected here - time to create a new AI - is exactly the same as previous one.

All metrics are collected and stored on flat csv files for later analysis. From there, parameters like average, standard deviation (and thus coefficient of variation) can be quickly extracted.

How is CloudBench different from SPECvirt?

A "SPECvirt Tile" seems to be the equivalent of a single CB scenario, with a fixed number of AIs. In this sense CB is more flexible given the fact that a scenario is composed by any number of different AIs, each with its own load variation characteristics. The key differences are that CB:

- Contributes VM life cycles
- Number of VMs can be varied in any way we want

Appendix D. Bibliography

Cooper, B. F., Silberstein, A., Tam, E., Ramakrishnan, R., & Sears, R. (2010). *Benchmarking Cloud Serving Systems with YCSB.* Santa Clara, CA, USA: Yahoo! Research.

Dumitras, T., & Shou, D. (2011). *Toward a Standard Benchmark for Computer Security Research.* Carnegie Mellon University.

Mell, P., & Grance, T. (2011, Sept). *NIST CSRC Special Publications*. Retrieved from NIST Computer Security Division: Computer Security Resource Center: http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf