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Abstract The Cloud computing emerges as a new computing paradigm which aims to provide reliable, customized and QoS guaranteed dynamic computing environments for end-users. In this paper, we study the Cloud computing paradigm from various aspects, such as definitions, distinct features, and enabling technologies. This paper brings an introductional review on the Cloud computing and provide the state-of-the-art of Cloud computing technologies.

Keywords Cloud Computing, Grid Computing, Cyberinfrastructure, Distributed Computing

§1 Introduction

The Cloud computing, which was coined in late of 2007, currently emerges as a hot topic due to its abilities to offer flexible dynamic IT infrastructures, QoS guaranteed computing environments and configurable software services. As reported in the Google trends shown in Figure 1, the Cloud computing (the blue

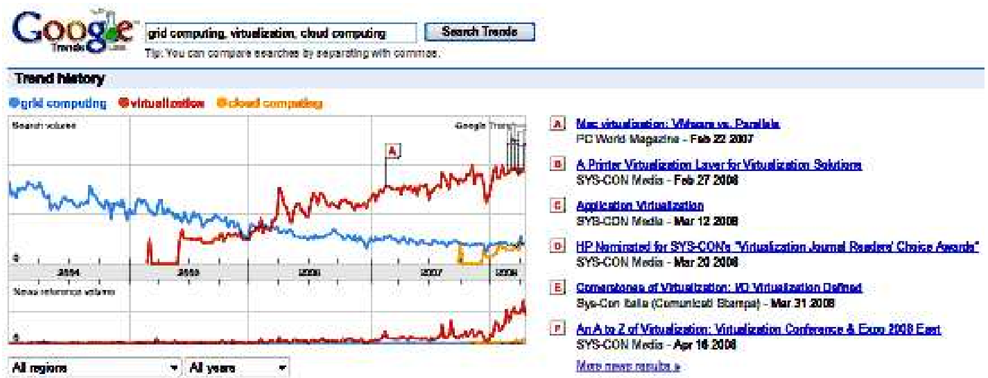

Fig. 1 Cloud computing in Google trends

line), which is enabled by virtualization technology (the yellow line), has already outpaced the Grid computing [8] (the red line).

Numerous projects within industry and academia have already started, for example the RESERVOIR project [27] – an IBM and European Union joint research initiative for Cloud computing, Amazon Elastic Compute Cloud [13], IBM's Blue Cloud [10], scientific Cloud projects such as Nimbus [24] and Stratus [31], and OpenNEbula [26]. HP, Intel Corporation and Yahoo! Inc. recently announced the creation of a global, multi-data center, open source Cloud computing test bed for industry, research and education [3].

There are still no widely accepted definitions for the Cloud computing albeit the Cloud computing practice has attracted much attention. Several reasons lead into this situation:

- Cloud computing involves researchers and engineers from various backgrounds, e.g., Grid computing, software engineering and database. They work on Cloud computing from different viewpoints.
- Technologies which enable the Cloud computing are still evolving and progressing, for example, Web 2.0 and Service Oriented Computing.
- Existing computing Clouds still lack large scale deployment and usage, which would finally justify the concept of Cloud computing.

In this paper we attempt to contribute the concept of Cloud computing: definition, functionality, enabling technology and typical applications. The remaining parts of this paper are organized as follows. Section 2 discusses the concept of Cloud computing, Section 3 presents the functionalities of the Cloud computing, Section 4 reviews the distinct features of the Cloud computing, and

Section 5 enumerates the enabling technologies for building computing Clouds. Section 6 concludes the whole paper.

§2 Definition of Cloud Computing

Cloud computing is becoming one of the next IT industry buzz words: users move out their data and applications to the remote "Cloud" and then access them in a simple and pervasive way. This is again a central processing use case. Similar scenario occurred around 50 years ago: a time-sharing computing server served multiple users. Until 20 years ago when personal computers came to us, data and programs were mostly located in local resources. Certainly currently the Cloud computing paradigm is not a recurrence of the history. 50 years ago we had to adopt the time-sharing servers due to limited computing resources. Nowadays the Cloud computing comes into fashion due to the need to build complex IT infrastructures. Users have to manage various software installations, configuration and updates. Computing resources and other hardware are prone to be outdated very soon. Therefore outsourcing computing platforms is a smart solution for users to handle complex IT infrastructures.

At the current stage, the Cloud computing is still evolving and there exists no widely accepted definition. Based on our experience, we propose an early definition of Cloud computing as follows:

> *A computing Cloud is a set of network enabled services, providing scalable, QoS guaranteed, normally personalized, inexpensive computing infrastructures on demand, which could be accessed in a simple and pervasive way.*

§3 Functional Aspects of Cloud Computing

Conceptually, users acquire computing platforms or IT infrastructures from computing Clouds and then run their applications inside. Therefore, computing Clouds render users with services to access hardware, software and data resources, thereafter an integrated computing platform as a service, in a transparent way:

Hardware as a Service (HaaS):

Hardware as a Service was coined possibly in 2006. As the result of rapid advances in hardware virtualization, IT automation and usage metering & pricing, users could buy IT hardware, or even an entire data center, as a pay-as-you-go subscription service. The HaaS is flexible, scalable and manageable to meet your needs [2]. Examples could be found at Amazon EC2 [13], IBM's Blue Cloud project [10], Nimbus [24], Eucalyptus [18] and Enomalism [17].

Software as a Service (SaaS):

Software or an application is hosted as a service and provided to customers across the Internet. This mode eliminates the need to install and run the application on the customer's local computers. SaaS therefore alleviates the customer's burden of software maintenance, and reduces the expense of software purchases by on-demand pricing. An early example of the SaaS is the Application Service Provider (ASP) [15]. The ASP approach provides subscriptions to software that is hosted or delivered over the Internet. Microsoft's "Software + Service" [30] shows another example: a combination of local software and Internet services interacting with one another. Google's Chrome browser [21] gives an interesting SaaS scenario: a new desktop could be offered, through which applications can be delivered (either locally or remotely) in addition to the traditional Web browsing experience.

Data as a Service (DaaS):

Data in various formats and from multiple sources could be accessed via services by users on the network. Users could, for example, manipulate the remote data just like operate on a local disk or access the data in a semantic way in the Internet.

Amazon Simple Storage Service (S3) [14] provides a simple Web services interface that can be used to store and retrieve, declared by Amazon, any amount of data, at any time, from anywhere on the Web. The DaaS could also be found at some popular IT services, e.g., Google Docs [22] and Adobe Buzzword [12]. ElasticDrive [16] is a distributed remote storage application which allows users to mount a remote storage resource such as Amazon S3 as a local storage device.

Based on the support of the HaaS, SaaS and DaaS, the Cloud computing in addition can deliver the Infrastructure as a Service (IaaS) for users. Users thus can on-demand subscribe to their favorite computing infrastructures with requirements of hardware configuration, software installation and data access demands. Figure 2 shows the relationship between the services. The Google

App Engine [20] is an interesting example of the IaaS. The Google App Engine enables users to build Web applications with Google's APIs and SDKs across the same scalable systems, which power the Google applications.

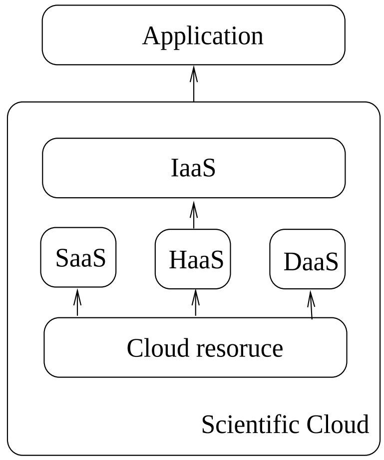

Fig. 2 Cloud functionalities

§4 Why is Cloud Computing Distinct?

The Cloud computing distinguishes itself from other computing paradigms, like Grid computing, Global computing, Internet Computing in the following aspects:

User-centric interfaces.

Cloud services should be accessed with simple and pervasive methods. In fact, the Cloud computing adopts the concept of Utility computing. In other words, users obtain and employ computing platforms in computing Clouds as easily as they access a traditional public utility (such as electricity, water, natural gas, or telephone network). In detail, the Cloud services enjoy the following features:

- The Cloud interfaces do not force users to change their working habits and environments, e.g., programming language, compiler and operating system. This feature differs Cloud computing from Grid computing as Grid users have to learn new Grid commands & APIs to access Grid resources & services.
- The Cloud client software which is required to be installed locally is lightweight. For example, the Nimbus Cloudkit client

size is around 15MB.

- Cloud interfaces are location independent and can be accessed by some well established interfaces like Web services framework and Internet browser.

On-demand service provisioning.

Computing Clouds provide resources and services for users on demand. Users can customize and personalize their computing environments later on, for example, software installation, network configuration, as users usually own administrative privileges.

QoS guaranteed offer.

The computing environments provided by computing Clouds can guarantee QoS for users, e.g., hardware performance like CPU speed, I/O bandwidth and memory size.

The computing Cloud renders QoS in general by processing Service Level Agrement (SLA) with users – a negotiation on the levels of availability, serviceability, performance, operation, or other attributes of the service like billing and even penalties in the case of violation of the SLA.

Autonomous System.

The computing Cloud is an autonomous system and it is managed transparently to users. Hardware, software and data inside clouds can be automatically reconfigured, orchestrated and consolidated to present a single platform image, finally rendered to users.

Scalability and flexibility.

The scalability and flexibility are the most important features that drive the emergence of the Cloud computing. Cloud services and computing platforms offered by computing Clouds could be scaled across various concerns, such as geographical locations, hardware performance, software configurations. The computing platforms should be flexible to adapt to various requirements of a potentially large number of users.

§5 Enabling Technologies behind Cloud Computing

A number of enabling technologies contribute to Cloud computing, several state-of-the-art techniques are identified here:

Virtualization technology.
Virtualization technologies partition hardware and thus provide flexible and scalable computing platforms. Virtual machine techniques, such as VMware [34] and Xen [1], offer virtualized IT-infrastructures on demand. Virtual network advances, such as VPN [7], support users with a customized network environment to access Cloud resources. Virtualization techniques are the bases of the Cloud computing since they render flexible and scalable hardware services.

Orchestration of service flow and workflow.
Computing Clouds offer a complete set of service templates on demand, which could be composed by services inside the computing Cloud. Computing Clouds therefore should be able to automatically orchestrate services from different sources and of different types to form a service flow or a workflow transparently and dynamically for users.

Web service and Service Oreinted Architecture (SOA).
Computing Cloud services are normally exposed as Web services, which follow the industry standards such as WSDL [33], SOAP [28] and UDDI [25]. The services organization and orchestration inside Clouds could be managed in a Service Oriented Architecture (SOA). A set of Cloud services furthermore could be used in a SOA application environment, thus making them available on various distributed platforms and could be further accessed across the Internet.

Web 2.0.
Web 2.0 is an emerging technology describing the innovative trends of using World Wide Web technology and Web design that aims to enhance creativity, information sharing, collaboration and functionality of the Web [6]. The essential idea behind Web 2.0 is to improve the interconnectivity and interactivity of Web applications. The new paradigm to develop and access Web applications enables users access the Web more easily and efficiently. Cloud computing services in nature are Web applications which render desirable computing services on demand. It is thus a natural technical evolution that the Cloud computing adopts the Web 2.0 technique.

World-wide distributed storage system.

A Cloud storage model should foresee:

- A network storage system, which is backed by distributed storage providers (e.g., data centers), offers storage capacity for users to lease. The data storage could be migrated, merged, and managed transparently to end users for whatever data formats. Examples are Google File System [9] and Amazon S3 [14]. A Mashup [11] is a Web application that combines data from more than one source into a single integrated storage tool. The SmugMug [29] is an example of Mashup, which is a digital photo sharing Web site, allowing the upload of an unlimited number of photos for all account types, providing a published API which allows programmers to create new functionality, and supporting XML-based RSS and Atom feeds.
- A distributed data system which provides data sources accessed in a semantic way. Users could locate data sources in a large distributed environment by the logical name instead of physical locations. Virtual Data System (VDS) [32] is good reference.

Programming model.

Users drive into the computing Cloud with data and applications. Some Cloud programming models should be proposed for users to adapt to the Cloud infrastructure. For the simplicity and easy access of Cloud services, the Cloud programming model, however, should not be too complex or too innovative for end users.

The MapReduce [4, 5] is a programming model and an associated implementation for processing and generating large data sets across the Google worldwide infrastructures. The MapReduce model firstly involves applying a "map" operation to some data records – a set of key/value pairs, and then processes a "reduce" operation to all the values that shared the same key. The Map-Reduce-Merge [35] method evolves the MapReduce paradigm by adding a "merge" operation. Hadoop [23] is a framework for running applications on large clusters built of commodity hardware. It implements the MapReduce paradigm and provides a distributed file system – the Hadoop Distributed File System. The MapReduce and the Hadoop are adopted by recently created international Cloud computing project of Yahoo!, Intel and HP [3, 19].

§6 Conclusion

This paper reviews the recent advances of Cloud computing and presents our views on Cloud computing: definition, key features and enabling technologies. The perspective study aims to contribute the evolution of the Cloud computing paradigm.

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