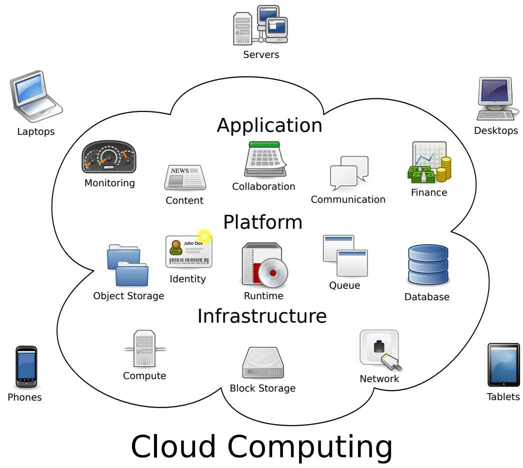
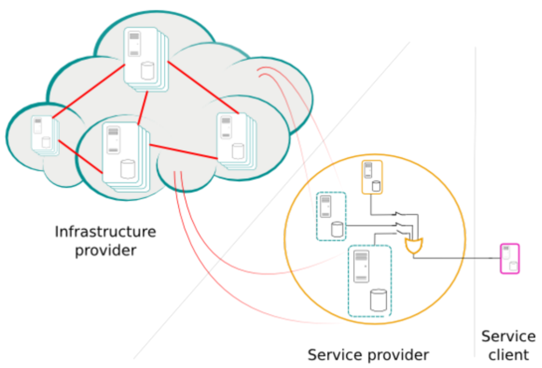
Cloud computing



Cloud computing metaphor: For a user, the network elements representing the provider-rendered services are invisible, as if obscured by a cloud.



Another representation of the cloud computing model. Here, the emphasis is on the delivery of a service.

Cloud computing is internet-based computing in which large groups of remote servers are networked to allow the centralized data storage, and online access to computer services or resources. Clouds can be classified as public, private or hybrid.*[1]

1 Overview

Cloud computing relies on sharing of resources to achieve coherence and economies of scale, similar to a utility (like the electricity grid) over a network.*[1] At the foundation of cloud computing is the broader concept of converged infrastructure and shared services.

Cloud computing, or in simpler shorthand just "the cloud", also focuses on maximizing the effectiveness of the shared resources. Cloud resources are usually not only shared by multiple users but are also dynamically reallocated per demand. This can work for allocating resources to users. For example, a cloud computer facility that serves European users during European business hours with a specific application (e.g., email) may reallocate the same resources to serve North American users during North America's business hours with a different application (e.g., a web server). This approach should maximize the use of computing power thus reducing environmental damage as well since less power, air conditioning, rackspace, etc. are required for a variety of functions. With cloud computing, multiple users can access a single server to retrieve and update their data without purchasing licenses for different applications.

The term "moving to cloud" also refers to an organization moving away from a traditional CAPEX model (buy the dedicated hardware and depreciate it over a period of time) to the OPEX model (use a shared cloud infrastructure and pay as one uses it).

Proponents claim that cloud computing allows companies to avoid upfront infrastructure costs, and focus on projects that differentiate their businesses instead of on infrastructure.*[2] Proponents also claim that cloud computing allows enterprises to get their applications up and running faster, with improved manageability and less maintenance, and enables IT to more rapidly adjust resources to meet fluctuating and unpredictable business demand.*[2]*[3]*[4] Cloud providers typically use a "pay as you go" model. This can lead to unexpectedly high charges if administrators do not adapt to the cloud pricing model.*[5]

The present availability of high-capacity networks, low-cost computers and storage devices as well as the widespread adoption of hardware virtualization, service-oriented architecture, and autonomic and utility computing have led to a growth in cloud computing.*[6]*[7]*[8]

Cloud vendors are experiencing growth rates of 50% per annum.*[9]

2 History

2.1 Origin of the term

The origin of the term *cloud computing* is unclear. The expression *cloud* is commonly used in science to describe a large agglomeration of objects that visually appear from a distance as a cloud and describes any set of things whose details are not inspected further in a given context.

In analogy to above usage the word *cloud* was used as a metaphor for the Internet and a standardized cloud-like shape was used to denote a network on telephony schematics and later to depict the Internet in computer network diagrams. With this simplification, the implication is that the specifics of how the end points of a network are connected are not relevant for the purposes of understanding the diagram. The cloud symbol was used to represent the Internet as early as 1994,*[10]*[11] in which servers were then shown connected to, but external to, the cloud.

References to cloud computing in its modern sense appeared early as 1996, with the earliest known mention in a Compaq internal document.*[12]

The popularization of the term can be traced to 2006 when Amazon.com introduced the Elastic Compute Cloud.*[13]

2.2 The 1950s

The underlying concept of cloud computing dates to the 1950s, when large-scale mainframe computers were seen as the future of computing, and became available in academia and corporations, accessible via thin clients/terminal computers, often referred to as “static terminals”, because they were used for communications but had no internal processing capacities. To make more efficient use of costly mainframes, a practice evolved that allowed multiple users to share both the physical access to the computer from multiple terminals as well as the CPU time. This eliminated periods of inactivity on the mainframe and allowed for a greater return on the investment. The practice of sharing CPU time on a mainframe became known in the industry as time-sharing.*[14] During the mid 70s, time-sharing was popularly known as RJE (Remote Job Entry); this nomenclature was mostly associated with large vendors such as IBM and DEC.

2.3 The 1990s

In the 1990s, telecommunications companies, who previously offered primarily dedicated point-to-point data circuits, began offering virtual private network (VPN) services with comparable quality of service, but at a lower cost. By switching traffic as they saw fit to balance server use, they could use overall network bandwidth more effectively. They began to use the cloud symbol to denote the demarcation point between what the provider was responsible for and what users were responsible for. Cloud computing extends this boundary to cover all servers as well as the network infrastructure.*[15]

As computers became more prevalent, scientists and technologists explored ways to make large-scale computing power available to more users through time-sharing. They experimented with algorithms to optimize the infrastructure, platform, and applications to prioritize CPUs and increase efficiency for end users.*[16]

2.4 Since 2000

In early 2008, Eucalyptus became the first open-source, AWS API-compatible platform for deploying private clouds. In early 2008, OpenNebula, enhanced in the RESERVOIR European Commission-funded project, became the first open-source software for deploying private and hybrid clouds, and for the federation of clouds.*[17] In the same year, efforts were focused on providing quality of service guarantees (as required by real-time interactive applications) to cloud-based infrastructures, in the framework of the IRMOS European Commission-funded project, resulting in a real-time cloud environment.*[18] By mid-2008, Gartner saw an opportunity for cloud computing “to shape the relationship among consumers of IT services, those who use IT services and those who sell them”*[19] and observed that “organizations are switching from company-owned hardware and software assets to per-use service-based models” so that the “projected shift to computing ... will result in dramatic growth in IT products in some areas and significant reductions in other areas.” *[20]

In July 2010, Rackspace Hosting and NASA jointly launched an open-source cloud-software initiative known as OpenStack. The OpenStack project intended to help organizations offer cloud-computing services running on standard hardware. The early code came from NASA's Nebula platform as well as from Rackspace's Cloud Files platform.*[21]

On March 1, 2011, IBM announced the IBM SmartCloud framework to support Smarter Planet.*[22] Among the various components of the Smarter Computing foundation, cloud computing is a critical piece.

On June 7, 2012, Oracle announced the Oracle Cloud.*[23] While aspects of the Oracle Cloud are still in development, this cloud offering is posed to be the first to provide users with access to an integrated set of IT solutions, including the Applications (SaaS), Platform (PaaS), and Infrastructure (IaaS) layers.*[24]*[25]*[26]

3 Similar concepts

Cloud computing is the result of evolution and adoption of existing technologies and paradigms. The goal of cloud computing is to allow users to take benefit from all of these technologies, without the need for deep knowledge about or expertise with each one of them. The cloud aims to cut costs, and help the users focus on their core business instead of being impeded by IT obstacles.*[27]

The main enabling technology for cloud computing is virtualization. Virtualization software separates a physical computing device into one or more "virtual" devices, each of which can be easily used and managed to perform computing tasks. With operating system–level virtualization essentially creating a scalable system of multiple independent computing devices, idle computing resources can be allocated and used more efficiently. Virtualization provides the agility required to speed up IT operations, and reduces cost by increasing infrastructure utilization. Autonomic computing automates the process through which the user can provision resources on-demand. By minimizing user involvement, automation speeds up the process, reduces labor costs and reduces the possibility of human errors.*[27]

Users routinely face difficult business problems. Cloud computing adopts concepts from Service-oriented Architecture (SOA) that can help the user break these problems into services that can be integrated to provide a solution. Cloud computing provides all of its resources as services, and makes use of the well-established standards and best practices gained in the domain of SOA to allow global and easy access to cloud services in a standardized way.

Cloud computing also leverages concepts from utility computing to provide metrics for the services used. Such metrics are at the core of the public cloud pay-per-use models. In addition, measured services are an essential part of the feedback loop in autonomic computing, allowing services to scale on-demand and to perform automatic failure recovery.

Cloud computing is a kind of grid computing; it has evolved by addressing the QoS (quality of service) and reliability problems. Cloud computing provides the tools and technologies to build data/compute intensive parallel applications with much more affordable prices compared to traditional parallel computing techniques.<ref name=HAM2012/

Cloud computing shares characteristics with:

- Client–server model —*Client–server computing* refers broadly to any distributed application that distinguishes between service providers (servers) and service requestors (clients).*[28]
- Grid computing — "A form of distributed and parallel computing, whereby a 'super and virtual computer' is composed of a cluster of networked, loosely coupled computers acting in concert to perform very large tasks."
- Mainframe computer —Powerful computers used mainly by large organizations for critical applications, typically bulk data processing such as: census; industry and consumer statistics; police and secret intelligence services; enterprise resource planning; and financial transaction processing.
- Utility computing —The "packaging of computing resources, such as computation and storage, as a metered service similar to a traditional public utility, such as electricity." *[29]*[30]
- Peer-to-peer —A distributed architecture without the need for central coordination. Participants are both suppliers and consumers of resources (in contrast to the traditional client–server model).

4 Characteristics

Cloud computing exhibits the following key characteristics:

- **Agility** improves with users' ability to re-provision technological infrastructure resources.
- **Application programming interface** (API) accessibility to software that enables machines to interact with cloud software in the same way that a traditional user interface (e.g., a computer desktop) facilitates interaction between humans and computers. Cloud computing systems typically use Representational State Transfer (REST)-based APIs.
- **Cost** reductions claimed by cloud providers. A public-cloud delivery model converts capital expenditure to operational expenditure.*[31] This purportedly lowers barriers to entry, as infrastructure is typically provided by a third party and does not need to be purchased for one-time or infrequent intensive computing tasks. Pricing on a utility computing basis is fine-grained, with usage-based options and fewer IT skills are required for implementation (in-house).*[32] The e-FISCAL project's state-of-the-art repository*[33] contains several articles looking into cost aspects in more detail, most of them concluding that costs savings depend on the type of

activities supported and the type of infrastructure available in-house.

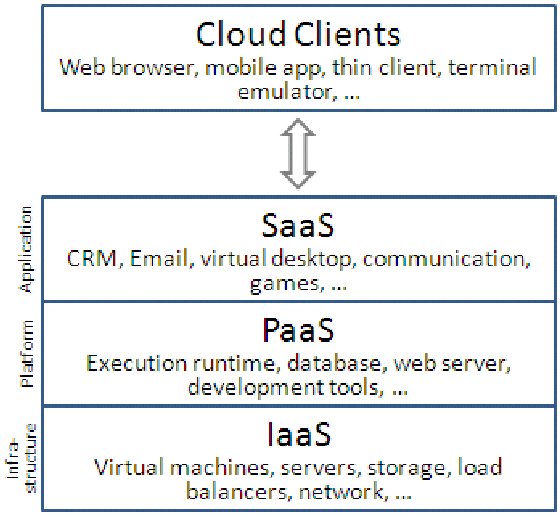
- **Device and location independence***[34] enable users to access systems using a web browser regardless of their location or what device they use (e.g., PC, mobile phone). As infrastructure is off-site (typically provided by a third-party) and accessed via the Internet, users can connect from anywhere.*[32]
- **Maintenance** of cloud computing applications is easier, because they do not need to be installed on each user's computer and can be accessed from different places.
- **Multitenancy** enables sharing of resources and costs across a large pool of users thus allowing for:
  - **centralization** of infrastructure in locations with lower costs (such as real estate, electricity, etc.)
  - **peak-load capacity** increases (users need not engineer for highest possible load-levels)
  - **utilisation and efficiency** improvements for systems that are often only 10–20% utilised.*[35]*[36]
- **Performance** is monitored, and consistent and loosely coupled architectures are constructed using web services as the system interface.*[32]*[37]*[38]
- **Productivity** may be increased when multiple users can work on the same data simultaneously, rather than waiting for it to be saved and emailed. Time may be saved as information does not need to be re-entered when fields are matched, nor do users need to install application software upgrades to their computer.*[39]
- **Reliability** improves with the use of multiple redundant sites, which makes well-designed cloud computing suitable for business continuity and disaster recovery.*[40]
- **Scalability and elasticity** via dynamic (“on-demand”) provisioning of resources on a fine-grained, self-service basis in near real-time*[41]*[42] (Note, the VM startup time varies by VM type, location, OS and cloud providers*[41]), without users having to engineer for peak loads.*[43]*[44]*[45]
- **Security** can improve due to centralization of data, increased security-focused resources, etc., but concerns can persist about loss of control over certain sensitive data, and the lack of security for stored kernels.*[46] Security is often as good as or better than other traditional systems, in part because providers are able to devote resources to solving security issues that many customers cannot afford to tackle.*[47] However, the complexity of security is greatly increased when data is distributed over a wider area or over a greater number of devices, as well as in multi-tenant systems shared by unrelated users. In addition, user access to security audit logs may be difficult or impossible. Private cloud installations are in part motivated by users' desire to retain control over the infrastructure and avoid losing control of information security.

The National Institute of Standards and Technology's definition of cloud computing identifies “five essential characteristics":

> *On-demand self-service.* A consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider.
>
> *Broad network access.* Capabilities are available over the network and accessed through standard mechanisms that promote use by heterogeneous thin or thick client platforms (e.g., mobile phones, tablets, laptops, and workstations).
>
> *Resource pooling.* The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand.
>
> *Rapid elasticity.* Capabilities can be elastically provisioned and released, in some cases automatically, to scale rapidly outward and inward commensurate with demand. To the consumer, the capabilities available for provisioning often appear unlimited and can be appropriated in any quantity at any time.
>
> *Measured service.* Cloud systems automatically control and optimize resource use by leveraging a metering capability at some level of abstraction appropriate to the type of service (e.g., storage, processing, bandwidth, and active user accounts). Resource usage can be monitored, controlled, and reported, providing transparency for both the provider and consumer of the utilized service.
>
> —National Institute of Standards and Technology*[1]

5 Service models

Cloud computing providers offer their services according to several fundamental models:*[1]*[48]



5.1 Infrastructure as a service (IaaS)

See also: Category:Cloud infrastructure and Software-defined application delivery

In the most basic cloud-service model & according to the IETF (Internet Engineering Task Force), providers of IaaS offer computers – physical or (more often) virtual machines – and other resources. (A hypervisor, such as Xen, Oracle VirtualBox, KVM, VMware ESX/ESXi, or Hyper-V runs the virtual machines as guests. Pools of hypervisors within the cloud operational support-system can support large numbers of virtual machines and the ability to scale services up and down according to customers' varying requirements.) IaaS clouds often offer additional resources such as a virtual-machine disk image library, raw block storage, and file or object storage, firewalls, load balancers, IP addresses, virtual local area networks (VLANs), and software bundles.*[49] IaaS-cloud providers supply these resources on-demand from their large pools installed in data centers. For wide-area connectivity, customers can use either the Internet or carrier clouds (dedicated virtual private networks).

To deploy their applications, cloud users install operating-system images and their application software on the cloud infrastructure. In this model, the cloud user patches and maintains the operating systems and the application software. Cloud providers typically bill IaaS services on a utility computing basis: cost reflects the amount of resources allocated and consumed.*[50]*[51]*[52]

5.2 Platform as a service (PaaS)

Main article: Platform as a service
See also: Category:Cloud platforms

In the PaaS models, cloud providers deliver a computing platform, typically including operating system, programming language execution environment, database, and web server. Application developers can develop and run their software solutions on a cloud platform without the cost and complexity of buying and managing the underlying hardware and software layers. With some PaaS offers like Microsoft Azure and Google App Engine, the underlying computer and storage resources scale automatically to match application demand so that the cloud user does not have to allocate resources manually. The latter has also been proposed by an architecture aiming to facilitate real-time in cloud environments.*[53]

Platform as a service (PaaS) provides a computing platform and a key chimney. It joins with software as a service (SaaS) and infrastructure as a service (IaaS), model of cloud computing.

5.3 Software as a service (SaaS)

Main article: Software as a service

In the business model using software as a service (SaaS), users are provided access to application software and databases. Cloud providers manage the infrastructure and platforms that run the applications. SaaS is sometimes referred to as "on-demand software" and is usually priced on a pay-per-use basis. SaaS providers generally price applications using a subscription fee.

In the SaaS model, cloud providers install and operate application software in the cloud and cloud users access the software from cloud clients. Cloud users do not manage the cloud infrastructure and platform where the application runs. This eliminates the need to install and run the application on the cloud user's own computers, which simplifies maintenance and support. Cloud applications are different from other applications in their scalability—which can be achieved by cloning tasks onto multiple virtual machines at run-time to meet changing work demand.*[54] Load balancers distribute the work over the set of virtual machines. This process is transparent to the cloud user, who sees only a single access point. To accommodate a large number of cloud users, cloud applications can be *multitenant*, that is, any machine serves more than one cloud user organization.

The pricing model for SaaS applications is typically a monthly or yearly flat fee per user,*[55] so price is scalable and adjustable if users are added or removed at any point.*[56]

Proponents claim SaaS allows a business the potential to reduce IT operational costs by outsourcing hardware and software maintenance and support to the cloud provider. This enables the business to reallocate IT operations costs away from hardware/software spending and personnel expenses, towards meeting other goals. In addition, with applications hosted centrally, updates can be released without the need for users to install new software. One drawback of SaaS is that the users' data are stored on the cloud provider's server. As a result, there could be unauthorized access to the data. For this reason, users are increasingly adopting intelligent third-party key management systems to help secure their data.

5.4 Unified Communications as a Service

Main article: Unified communications

In the UCaaS model, multi-platform communications over the network are packaged by the service provider. The services could be in different devices, such as computers and mobile devices. Services may include IP telephony, unified messaging, video conferencing and mobile extension*[57] etc.

6 Cloud clients

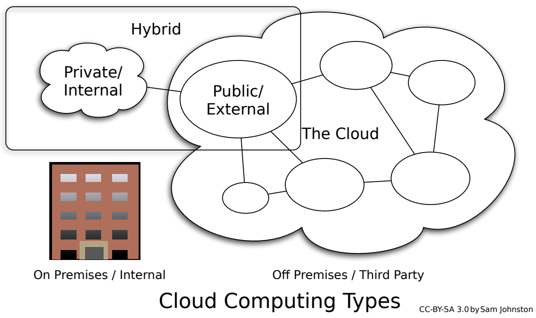
See also: Category:Cloud clients

Users access cloud computing using networked client devices, such as desktop computers, laptops, tablets and smartphones. Some of these devices – *cloud clients* – rely on cloud computing for all or a majority of their applications so as to be essentially useless without it. Examples are thin clients and the browser-based Chromebook. Many cloud applications do not require specific software on the client and instead use a web browser to interact with the cloud application. With Ajax and HTML5 these Web user interfaces can achieve a similar, or even better, look and feel to native applications. Some cloud applications, however, support specific client software dedicated to these applications (e.g., virtual desktop clients and most email clients). Some legacy applications (line of business applications that until now have been prevalent in thin client computing) are delivered via a screen-sharing technology.

7 Deployment models

7.1 Private cloud

Private cloud is cloud infrastructure operated solely for a single organization, whether managed internally or by a third-party, and hosted either internally or externally.*[1] Undertaking a private cloud project requires a significant level and degree of engagement to virtualize the business environment, and requires the organization to reevaluate decisions about existing resources. When done right, it can improve business, but every step in the project raises security issues that must be addressed to prevent serious



Cloud computing types

vulnerabilities.*[58] Self-run data centers*[59] are generally capital intensive. They have a significant physical footprint, requiring allocations of space, hardware, and environmental controls. These assets have to be refreshed periodically, resulting in additional capital expenditures. They have attracted criticism because users "still have to buy, build, and manage them" and thus do not benefit from less hands-on management,*[60] essentially "[lacking] the economic model that makes cloud computing such an intriguing concept" .*[61]*[62]

7.2 Public cloud

A cloud is called a "public cloud" when the services are rendered over a network that is open for public use. Public cloud services may be free or offered on a pay-per-usage model.*[63] Technically there may be little or no difference between public and private cloud architecture, however, security consideration may be substantially different for services (applications, storage, and other resources) that are made available by a service provider for a public audience and when communication is effected over a non-trusted network. Generally, public cloud service providers like Amazon AWS, Microsoft and Google own and operate the infrastructure at their data center and access is generally via the Internet. AWS and Microsoft also offer direct connect services called "AWS Direct Connect" and "Azure ExpressRoute" respectively, such connections require customers to purchase or lease a private connection to a peering point offered by the cloud provider.*[32]

7.3 Hybrid cloud

Hybrid cloud is a composition of two or more clouds (private, community or public) that remain distinct entities but are bound together, offering the benefits of multiple deployment models. Hybrid cloud can also mean the ability to connect collocation, managed and/or dedicated services with cloud resources.*[1]

Gartner, Inc. defines a hybrid cloud service as a cloud computing service that is composed of some combination of private, public and community cloud services, from different service providers.*[64] A hybrid cloud service crosses isolation and provider boundaries so that it can't be simply put in one category of private, public, or community cloud service. It allows one to extend either the capacity or the capability of a cloud service, by aggregation, integration or customization with another cloud service.

Varied use cases for hybrid cloud composition exist. For example, an organization may store sensitive client data in house on a private cloud application, but interconnect that application to a business intelligence application provided on a public cloud as a software service.*[65] This example of hybrid cloud extends the capabilities of the enterprise to deliver a specific business service through the addition of externally available public cloud services.

Another example of hybrid cloud is one where IT organizations use public cloud computing resources to meet temporary capacity needs that can not be met by the private cloud.*[66] This capability enables hybrid clouds to employ cloud bursting for scaling across clouds.*[1] Cloud bursting is an application deployment model in which an application runs in a private cloud or data center and "bursts" to a public cloud when the demand for computing capacity increases. A primary advantage of cloud bursting and a hybrid cloud model is that an organization only pays for extra compute resources when they are needed.*[67] Cloud bursting enables data centers to create an in-house IT infrastructure that supports average workloads, and use cloud resources from public or private clouds, during spikes in processing demands.*[68]

7.4 Others

7.4.1 Community cloud

Community cloud shares infrastructure between several organizations from a specific community with common concerns (security, compliance, jurisdiction, etc.), whether managed internally or by a third-party, and either hosted internally or externally. The costs are spread over fewer users than a public cloud (but more than a private cloud), so only some of the cost savings potential of cloud computing are realized.*[1]

7.4.2 Distributed cloud

Cloud computing can also be provided by a distributed set of machines that are running at different locations, while still connected to a single network or hub service. Examples of this include distributed computing platforms such as BOINC and Folding@Home. An interesting attempt in such direction is Cloud@Home, aiming at implementing cloud computing provisioning model on top of voluntarily shared resources *[69]

7.4.3 Intercloud

Main article: Intercloud

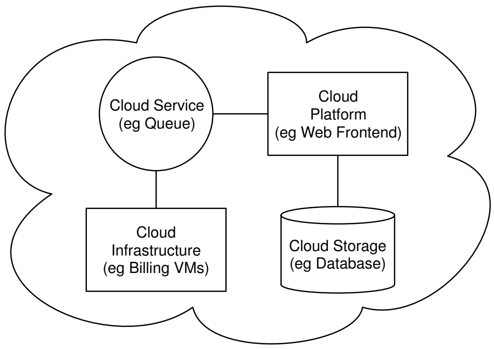
The Intercloud*[70] is an interconnected global "cloud of clouds" *[71]*[72] and an extension of the Internet "network of networks" on which it is based. The focus is on direct interoperability between public cloud service providers, more so than between providers and consumers (as is the case for hybrid- and multi-cloud).*[73]*[74]*[75]

7.4.4 Multicloud

Main article: Multicloud

Multicloud is the use of multiple cloud computing services in a single heterogeneous architecture to reduce reliance on single vendors, increase flexibility through choice, mitigate against disasters, etc. It differs from hybrid cloud in that it refers to multiple cloud services, rather than multiple deployment modes (public, private, legacy).*[76]*[77]

8 Architecture



Cloud computing sample architecture

Cloud architecture,*[78] the systems architecture of the software systems involved in the delivery of cloud computing, typically involves multiple *cloud components* communicating with each other over a loose coupling mechanism such as a messaging queue. Elastic provision implies intelligence in the use of tight or loose coupling as applied to mechanisms such as these and others.

8.1 Cloud engineering

Cloud engineering is the application of engineering disciplines to cloud computing. It brings a systematic approach to the high-level concerns of commercialization, standardization, and governance in conceiving, developing, operating and maintaining cloud computing systems. It is a multidisciplinary method encompassing contributions from diverse areas such as systems, software, web, performance, information, security, platform, risk, and quality engineering.

9 Security, privacy and trust

Main article: Cloud computing issues

Across all forms of deployment, architecture and service models the basic concept of cloud computing remains to be the abstraction of computation over the used hardware/resources. If considering various groups of stakeholders, a three-tier setup can be considered: i) users of virtual services ii) tenants who provide services iii) providers who provide the infrastructure. The key to gaining trust in cloud computing is assuring the user or tenant of security being applied and maintained in all components contributing to his virtual service. Assuring security properties of the overall system to the service-user at the top level and considering the abstraction of computation over used hardware between all the levels makes assurance of security properties for a virtual service a very complex task. As privacy must not be comprised by revealing too much information between layers some inter level/stakeholder interfaces are required. A list of existing approaches can be found here *[79] Fundamentally private cloud is seen as more secure with higher levels of control for the owner, however public cloud is seen to be more flexible and requires less time and money investment from the user. *[80]

10 The future

According to Gartner's Hype cycle, cloud computing has reached a maturity that leads it into a productive phase. This means that most of the main issues with cloud computing have been addressed to a degree that clouds have become interesting for full commercial exploitation. This however does not mean that all the problems listed above have actually been solved, only that the according risks can be tolerated to a certain degree.*[81] Cloud computing is therefore still as much a research topic, as it is a market offering.*[82] What is clear through the evolution of Cloud Computing services is that the CTO is a major driving force behind Cloud adoption.*[83] The major Cloud technology developers continue to invest $billions a year in Cloud R&D, in 2011 Microsoft for example committed 90% of its $9.6bn R&D budget to Cloud*[84]

11 See also

- Cloud computing comparison
- Category:Cloud computing providers
- Grid computing
- Mobile cloud computing
- Personal cloud
- Cloud research
- Cloud management
- Web computing
- Category:Cloud platforms

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