U19ITE07	VIRTUALIZATION AND CLOUD COMPUTING	L	T	P	C
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Pre-Requisites : U19CSE03, U19ITE04

Objectives:

- To impart the fundamentals and essentials of Cloud Computing.
- To study about virtualization and cloud resource management.
- To provide a sound foundation of the Cloud Computing Services and tools
- To be aware of different cloud platforms.
- To study the core issues of cloud security and to understand various cloud applications.

Course Outcomes:

At the end of this course students will demonstrate the ability to

CO 1 : Articulate the main concepts, key technologies, strengths and limitations of cloud computing.

CO 2 : Explain the concept of cloud resource virtualization.

CO 3 : Apply the fundamental concepts in datacenters to understand the tradeoffs in power, efficiency and cost.

CO 4 : Choose the appropriate technologies, algorithms and approaches for implementation and use of cloud

CO 5 : Create and deploy cloud applications.

Unit I INTRODUCTION 9

Introduction - Overview of Computing Paradigms - The Cloud Computing reference model - Benefits and Characteristics of Cloud- Challenges - Cloud Computing Architecture - Cloud computing stack Service Models: Infrastructure as a Service, Platform as a Service, Software as a Service- Deployment Models: Public cloud, Private cloud, Hybrid cloud – Challenges

Unit II CLOUD RESOURCE VIRTUALIZATION 9

Introduction to virtualization - Characteristics of virtualized environments- Taxonomy of virtualization techniques- Virtualization and cloud computing- Pros and cons of virtualization - Examples - Virtual Machine Provisioning and Manageability - VM Migration-Management of VM: Anatomy of cloud infrastructures - Scheduling techniques.

Unit III CLOUD PLATFORM ARCHITECTURES OVER VIRTUALIZED DATA CENTERS 9

Data-Center design and Interconnection networks - Architectural Design of Compute and Storage Clouds - Public Cloud Platforms, GAE, AWS, Azure - Inter-cloud Resource Management - Cloud Security and Trust Management.

Unit IV CLOUD PROGRAMMING AND SOFTWARE ENVIRONMENTS 9

Features of Cloud and Grid Platforms - Parallel and Distributed Programming Paradigms - Programming Support of Google App Engine - Programming on Amazon AWS and Microsoft Azure - Emerging Cloud Software Environments.Case Studies: Open stack, Heroku, and Docker Containers –Amazon EC2, Google Compute Engine.

Unit V CLOUD SECURITY & APPLICATIONS 9

Cloud Security Risks, Trust, Operating System Security, VM Security, Security of Virtualization, Security Risks Posted by Shared Images, Security Risks Posted by Management OS, Data privacy and security issues, Identity and Access Management , Access Control , Authentication in cloud computing - Applications: Scientific Applications - Business and Consumer Applications

Total Periods: 45

3. Pitney Bowes, an e-commerce company, offers clients the opportunity to perform B2B transactions using the Microsoft Azure platform, along with .NET and SQL services. These offerings have significantly increased the company's client base.

4.1.4.3 Mashup of Cloud Services

At the time of this writing, public clouds are in use by a growing number of users. Due to the lack of trust in leaking sensitive data in the business world, more and more enterprises, organizations, and communities are developing private clouds that demand deep customization. An enterprise cloud is used by multiple users within an organization. Each user may build some strategic applications on the cloud, and demands customized partitioning of the data, logic, and database in the metadata representation. More private clouds may appear in the future.

Based on a 2010 Google search survey, interest in grid computing is declining rapidly. *Cloud mashups* have resulted from the need to use multiple clouds simultaneously or in sequence. For example, an industrial supply chain may involve the use of different cloud resources or services at different stages of the chain. Some public repository provides thousands of service APIs and mashups for web commerce services. Popular APIs are provided by Google Maps, Twitter, YouTube, Amazon eCommerce, Salesforce.com, etc.

4.2 DATA-CENTER DESIGN AND INTERCONNECTION NETWORKS

A data center is often built with a large number of servers through a huge interconnection network. In this section, we will study the design of large-scale data centers and small modular data centers that can be housed in a 40-ft truck container. Then we will take a look at interconnection of modular data centers and their management issues and solutions.

4.2.1 Warehouse-Scale Data-Center Design

Dennis Gannon claims: "The cloud is built on massive datacenters" [26]. Figure 4.8 shows a data center that is as large as a shopping mall (11 times the size of a football field) under one roof. Such a data center can house 400,000 to 1 million servers. The data centers are built economics of scale—meaning lower unit cost for larger data centers. A small data center could have 1,000 servers. The larger the data center, the lower the operational cost. The approximate monthly cost to operate a huge 400-server data center is estimated by network cost $13/Mbps; storage cost $0.4/GB; and administration costs. These unit costs are greater than those of a 1,000-server data center. The network cost to operate a small data center is about seven times greater and the storage cost is 5.7 times greater. Microsoft has about 100 data centers, large or small, which are distributed around the globe.

4.2.1.1 Data-Center Construction Requirements

Most data centers are built with commercially available components. An off-the-shelf server consists of a number of processor sockets, each with a multicore CPU and its internal cache hierarchy, local shared and coherent DRAM, and a number of directly attached disk drives. The DRAM and disk resources within the rack are accessible through first-level rack switches and all resources in all

FIGURE 4.8

A huge data center that is 11 times the size of a football field, housing 400,000 to 1 million servers.

(*Courtesy of Dennis Gannon [26]*)

racks are accessible via a cluster-level switch. Consider a data center built with 2,000 servers, each with 8 GB of DRAM and four 1 TB disk drives. Each group of 40 servers is connected through a 1 Gbps link to a rack-level switch that has an additional eight 1 Gbps ports used for connecting the rack to the cluster-level switch.

It was estimated [9] that the bandwidth available from local disks is 200 MB/s, whereas the bandwidth from off-rack disks is 25 MB/s via shared rack uplinks. The total disk storage in the cluster is almost 10 million times larger than local DRAM. A large application must deal with large discrepancies in latency, bandwidth, and capacity. In a very large-scale data center, components are relatively cheaper. The components used in data centers are very different from those in building supercomputer systems.

With a scale of thousands of servers, concurrent failure, either hardware failure or software failure, of 1 percent of nodes is common. Many failures can happen in hardware; for example, CPU failure, disk I/O failure, and network failure. It is even quite possible that the whole data center does not work in the case of a power crash. Also, some failures are brought on by software. The service and data should not be lost in a failure situation. Reliability can be achieved by redundant hardware. The software must keep multiple copies of data in different locations and keep the data accessible while facing hardware or software errors.

4.2.1.2 Cooling System of a Data-Center Room

Figure 4.9 shows the layout and cooling facility of a warehouse in a data center. The data-center room has raised floors for hiding cables, power lines, and cooling supplies. The cooling system is somewhat simpler than the power system. The raised floor has a steel grid resting on stanchions

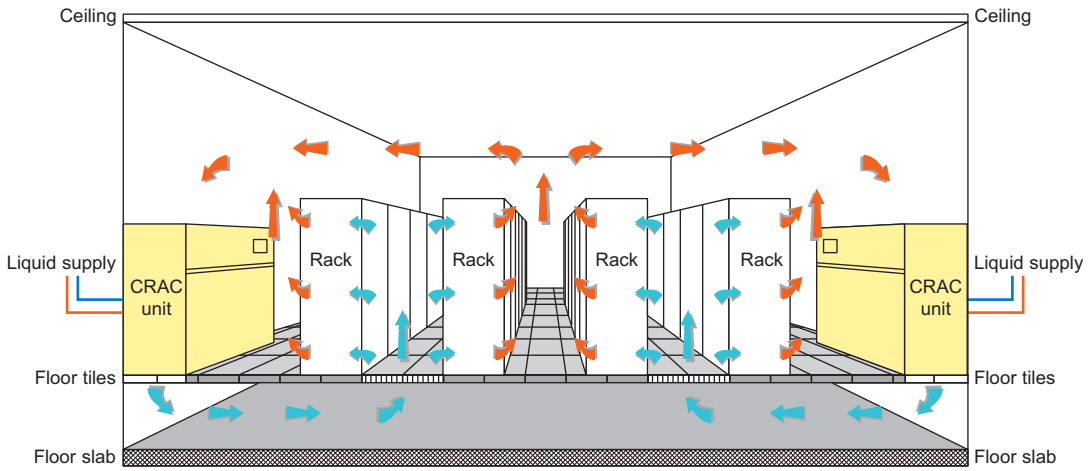


FIGURE 4.9

The cooling system in a raised-floor data center with hot-cold air circulation supporting water heat exchange facilities.

(*Courtesy of DLB Associates, D. Dyer [22]*)

about 2–4 ft above the concrete floor. The under-floor area is often used to route power cables to racks, but its primary use is to distribute cool air to the server rack. The CRAC (*computer room air conditioning*) unit pressurizes the raised floor plenum by blowing cold air into the plenum.

The cold air escapes from the plenum through perforated tiles that are placed in front of server racks. Racks are arranged in long aisles that alternate between cold aisles and hot aisles to avoid mixing hot and cold air. The hot air produced by the servers circulates back to the intakes of the CRAC units that cool it and then exhaust the cool air into the raised floor plenum again. Typically, the incoming coolant is at 12–14°C and the warm coolant returns to a chiller. Newer data centers often insert a cooling tower to pre-cool the condenser water loop fluid. Water-based free cooling uses cooling towers to dissipate heat. The cooling towers use a separate cooling loop in which water absorbs the coolant's heat in a heat exchanger.

4.2.2 Data-Center Interconnection Networks

A critical core design of a data center is the interconnection network among all servers in the data-center cluster. This network design must meet five special requirements: low latency, high bandwidth, low cost, *message-passing interface* (MPI) communication support, and fault tolerance. The design of an inter-server network must satisfy both point-to-point and collective communication patterns among all server nodes. Specific design considerations are given in the following sections.

4.2.2.1 Application Traffic Support

The network topology should support all MPI communication patterns. Both point-to-point and collective MPI communications must be supported. The network should have high bisection bandwidth

to meet this requirement. For example, one-to-many communications are used for supporting distributed file access. One can use one or a few servers as metadata master servers which need to communicate with slave server nodes in the cluster. To support the MapReduce programming paradigm, the network must be designed to perform the map and reduce functions (to be treated in Chapter 7) at a high speed. In other words, the underlying network structure should support various network traffic patterns demanded by user applications.

4.2.2.2 Network Expandability

The interconnection network should be expandable. With thousands or even hundreds of thousands of server nodes, the cluster network interconnection should be allowed to expand once more servers are added to the data center. The network topology should be restructured while facing such expected growth in the future. Also, the network should be designed to support load balancing and data movement among the servers. None of the links should become a bottleneck that slows down application performance. The topology of the interconnection should avoid such bottlenecks.

The fat-tree and crossbar networks studied in Chapter 2 could be implemented with low-cost Ethernet switches. However, the design could be very challenging when the number of servers increases sharply. The most critical issue regarding expandability is support of modular network growth for building data-center containers, as discussed in Section 4.2.3. One single data-center container contains hundreds of servers and is considered to be the building block of large-scale data centers. The network interconnection among many containers will be explained in Section 4.2.4. Cluster networks need to be designed for data-center containers. Cable connections are then needed among multiple data-center containers.

Data centers are not built by piling up servers in multiple racks today. Instead, data-center owners buy server containers while each container contains several hundred or even thousands of server nodes. The owners can just plug in the power supply, outside connection link, and cooling water, and the whole system will just work. This is quite efficient and reduces the cost of purchasing and maintaining servers. One approach is to establish the connection backbone first and then extend the backbone links to reach the end servers. One can also connect multiple containers through external switching and cabling.

4.2.2.3 Fault Tolerance and Graceful Degradation

The interconnection network should provide some mechanism to tolerate link or switch failures. In addition, multiple paths should be established between any two server nodes in a data center. Fault tolerance of servers is achieved by replicating data and computing among redundant servers. Similar redundancy technology should apply to the network structure. Both software and hardware network redundancy apply to cope with potential failures. One the software side, the software layer should be aware of network failures. Packet forwarding should avoid using broken links. The network support software drivers should handle this transparently without affecting cloud operations.

In case of failures, the network structure should degrade gracefully amid limited node failures. Hot-swappable components are desired. There should be no critical paths or critical points which may become a single point of failure that pulls down the entire system. Most design innovations are in the topology structure of the network. The network structure is often divided into two layers. The lower layer is close to the end servers, and the upper layer establishes the backbone connections among the server groups or sub-clusters. This hierarchical interconnection approach appeals to building data centers with modular containers.

4.2.2.4 Switch-centric Data-Center Design

At the time of this writing, there are two approaches to building data-center-scale networks: One is switch-centric and the other is server-centric. In a switch-centric network, the switches are used to connect the server nodes. The switch-centric design does not affect the server side. No modifications to the servers are needed. The server-centric design does modify the operating system running on the servers. Special drivers are designed for relaying the traffic. Switches still have to be organized to achieve the connections.

Example 4.4 A Fat-Tree Interconnection Network for Data Centers

Figure 4.10 shows a fat-tree switch network design for data-center construction. The fat-tree topology is applied to interconnect the server nodes. The topology is organized into two layers. Server nodes are in the bottom layer, and *edge switches* are used to connect the nodes in the bottom layer. The upper layer aggregates the lower-layer edge switches. A group of aggregation switches, edge switches, and their leaf nodes form a *pod*. *Core switches* provide paths among different pods. The fat-tree structure provides multiple paths between any two server nodes. This provides fault-tolerant capability with an alternate path in case of some isolated link failures.

The failure of an aggregation switch and core switch will not affect the connectivity of the whole network. The failure of any edge switch can only affect a small number of end server nodes. The extra switches in a pod provide higher bandwidth to support cloud applications in massive data movement. The building blocks used are the low-cost Ethernet switches. This reduces the cost quite a bit. The routing table provides extra routing paths in case of failure. The routing algorithms are built inside the switches. The end server nodes in the data center are not affected during a switch failure, as long as the alternate routing path does not fail at the same time.

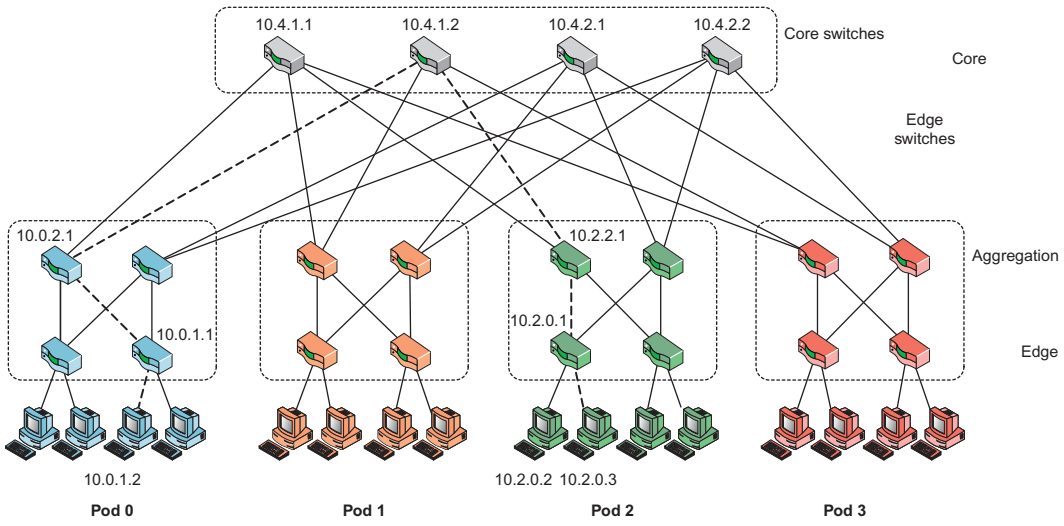


FIGURE 4.10

A fat-tree interconnection topology for scalable data-center construction.

(*Courtesy of M. Al-Fares, et al. [2]*)

4.2.3 Modular Data Center in Shipping Containers

A modern data center is structured as a shipyard of server clusters housed in truck-towed containers. Figure 4.11 shows the housing of multiple sever racks in a truck-towed container in the SGI ICE Cube modular data center. Inside the container, hundreds of blade servers are housed in racks surrounding the container walls. An array of fans forces the heated air generated by the server racks to go through a heat exchanger, which cools the air for the next rack (detail in callout) on a continuous loop. The SGI ICE Cube container can house 46,080 processing cores or 30 PB of storage per container.

Large-scale data center built with modular containers appear as a big shipping yard of container trucks. This container-based data center was motivated by demand for lower power consumption, higher computer density, and mobility to relocate data centers to better locations with lower electricity costs, better cooling water supplies, and cheaper housing for maintenance engineers. Sophisticated cooling technology enables up to 80% reduction in cooling costs compared with traditional warehouse data centers. Both chilled air circulation and cold water are flowing through the heat exchange pipes to keep the server racks cool and easy to repair.

Data centers usually are built at a site where leases and utilities for electricity are cheaper, and cooling is more efficient. Both warehouse-scale and modular data centers in containers are needed. In fact, the modular truck containers can be used to put together a large-scale data center like a container shipping yard. In addition to location selection and power savings in data-center operations, one must consider data integrity, server monitoring, and security management in data centers. These problems are easier to handle if the data center is centralized in a single large building.

4.2.3.1 Container Data-Center Construction

The data-center module is housed in a truck-towable container. The modular container design includes the network, computer, storage, and cooling gear. One needs to increase cooling efficiency by varying the water and airflow with better airflow management. Another concern is to meet seasonal load requirements. The construction of a container-based data center may start with one system (server), then move to a rack system design, and finally to a container system. This staged development may take different amounts of time and demand increasing costs. Building a rack of 40 servers may

FIGURE 4.11

A modular data center built in a truck-towed ICE Cube container, that can be cooled by chilled air circulation with cold-water heat exchanges.

(*Courtesy of SGI, Inc., http://www.sgi.com/icecube*)

take half a day. Extending this to a whole container system with multiple racks for 1,000 servers requires the layout of the floor space with power, networking, cooling, and complete testing.

The container must be designed to be weatherproof and easy to transport. Modular data-center construction and testing may take a few days to complete if all components are available and power and water supplies are handy. The modular data-center approach supports many cloud service applications. For example, the health care industry will benefit by installing a data center at all clinic sites. However, how to exchange information with the central database and maintain periodic consistency becomes a rather challenging design issue in a hierarchically structured data center. The security of collocation cloud services may involve multiple data centers.

4.2.4 Interconnection of Modular Data Centers

Container-based data-center modules are meant for construction of even larger data centers using a farm of container modules. Some proposed designs of container modules are presented in this section. Their interconnections are shown for building scalable data centers. The following example is a server-centric design of the data-center module.

Example 4.5 A Server-Centric Network for a Modular Data Center

Guo, et al. [30] have developed a server-centric BCube network (Figure 4.12) for interconnecting modular data centers. The servers are represented by circles, and switches by rectangles. The BCube provides a layered structure. The bottom layer contains all the server nodes and they form Level 0. Level 1 switches form the top layer of $BCube_0$. BCube is a recursively constructed structure. The $BCube_0$ consists of n servers connecting to an n-port switch. The $BCube_k$ ($k \geq 1$) is structured from n $BCube_{k-1}$ with n^k n-port switches. The example of $BCube_1$ is illustrated in Figure 4.12, where the connection rule is that the i-th server in the j-th $BCube_0$ connects to the j-th port of the i-th Level 1 switch. The servers in the BCube have multiple ports attached. This allows extra devices to be used in the server.

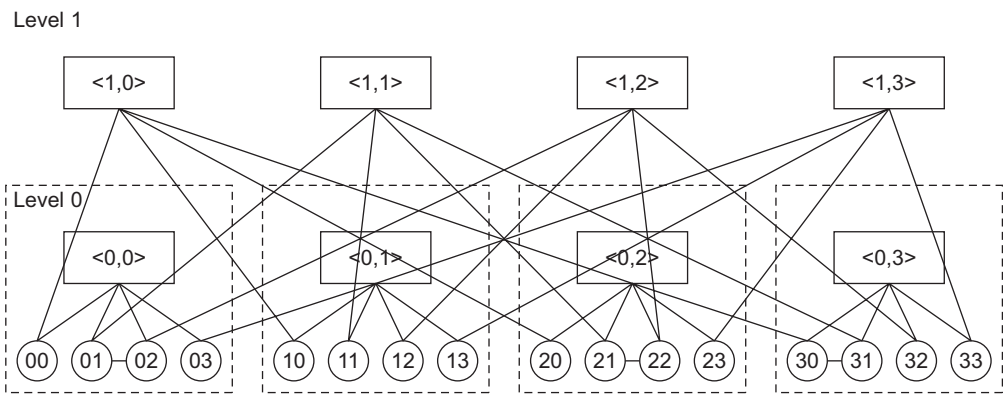


FIGURE 4.12

BCube, a high-performance, server-centric network for building modular data centers.

(*Courtesy of C. Guo, et al. [30]*)

The BCube provides multiple paths between any two nodes. Multiple paths provide extra bandwidth to support communication patterns in different cloud applications. The BCube provides a kernel module in the server OS to perform routing operations. The kernel module supports packet forwarding while the incoming packets are not destined to the current node. Such modification of the kernel will not influence the upper layer applications. Thus, the cloud application can still run on top of the BCube network structure without any modification.

4.2.4.1 Inter-Module Connection Networks

The BCube is commonly used inside a server container. The containers are considered the building blocks for data centers. Thus, despite the design of the inner container network, one needs another level of networking among multiple containers. In Figure 4.13, Wu, et al. [82] have proposed a network topology for intercontainer connection using the aforementioned BCube network as building blocks. The proposed network was named MDCube (for *Modularized Datacenter Cube*). This network connects multiple BCube containers by using high-speed switches in the BCube. Similarly, the MDCube is constructed by shuffling networks with multiple containers. Figure 4.13 shows how a 2D MDCube is constructed from nine $BCube_1$ containers.

The architecture builds a virtual hypercube at the container level, in addition to the cube structure inside the container (BCube). With the server container built with the BCube network, the MDCube is used to build a large-scale data center for supporting cloud application communication patterns. Readers are referred to the article at [45] for detailed implementation and simulation results of this interconnection network over multiple modular data centers built in containers. In fact, there are many other ways to use MDCube to build the network. Essentially, this network architecture builds a virtual hypercube at the container level, in addition to the cube structure inside the container (BCube). With the server container built with the BCube network, the MDCube is used to build a large-scale data center for supporting cloud application communication patterns [82].

4.2.5 Data-Center Management Issues

Here are basic requirements for managing the resources of a data center. These suggestions have resulted from the design and operational experiences of many data centers in the IT and service industries.

- **Making common users happy** The data center should be designed to provide quality service to the majority of users for at least 30 years.
- **Controlled information flow** Information flow should be streamlined. Sustained services and high availability (HA) are the primary goals.
- **Multiuser manageability** The system must be managed to support all functions of a data center, including traffic flow, database updating, and server maintenance.
- **Scalability to prepare for database growth** The system should allow growth as workload increases. The storage, processing, I/O, power, and cooling subsystems should be scalable.
- **Reliability in virtualized infrastructure** Failover, fault tolerance, and VM live migration should be integrated to enable recovery of critical applications from failures or disasters.

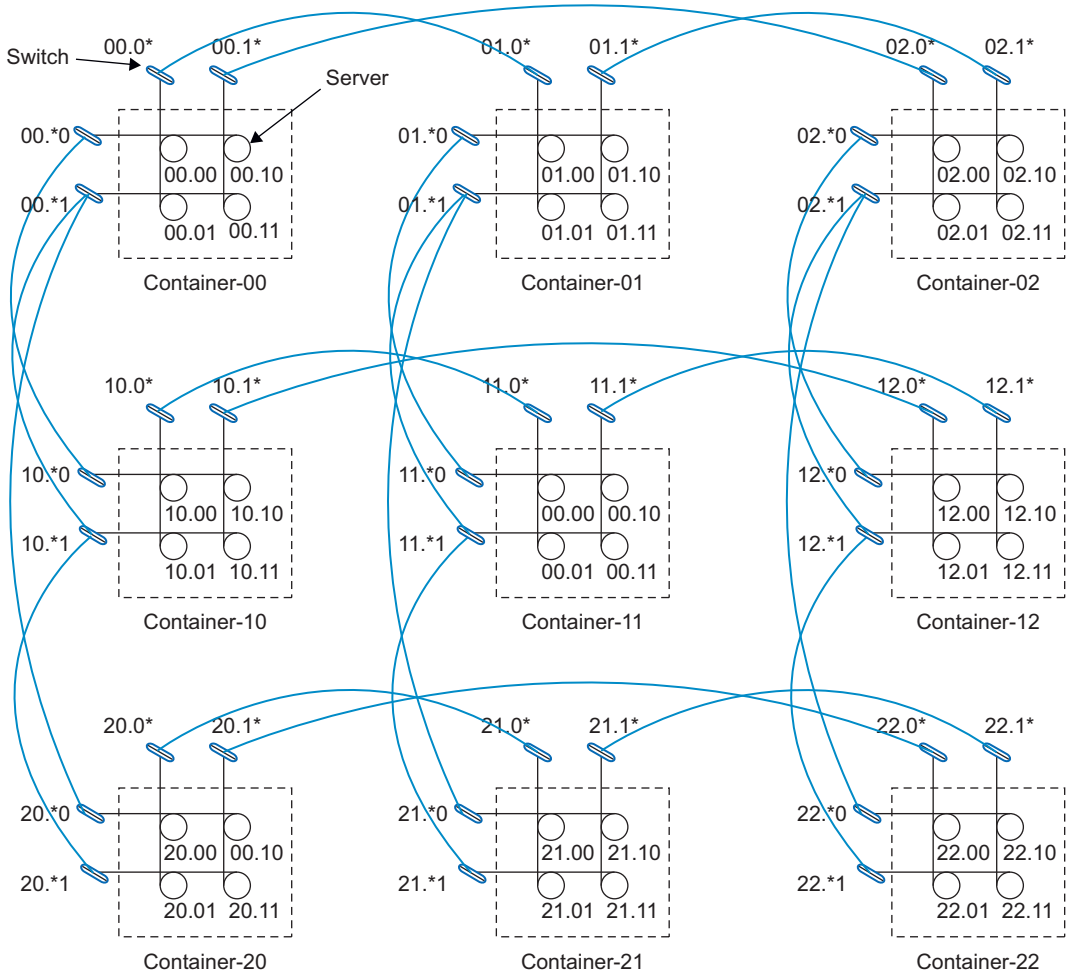


FIGURE 4.13

A 2D MDCube constructed from nine BCube containers.

(*Courtesy of Wu, et al. [82]*)

- **Low cost to both users and providers** The cost to users and providers of the cloud system built over the data centers should be reduced, including all operational costs.
- **Security enforcement and data protection** Data privacy and security defense mechanisms must be deployed to protect the data center against network attacks and system interrupts and to maintain data integrity from user abuses or network attacks.
- **Green information technology** Saving power consumption and upgrading energy efficiency are in high demand when designing and operating current and future data centers.

4.2.5.1 Marketplaces in Cloud Computing Services

Container-based data-center implementation can be done more efficiently with factory racking, stacking, and packing. One should avoid layers of packaging at the customer site. However, the data centers are still custom-crafted rather than prefab units. The modular approach is more space-efficient with power densities in excess of 1250 W/sq ft. Rooftop or parking lot installation is acceptable. One should leave sufficient redundancy to allow upgrades over time.

4.3 ARCHITECTURAL DESIGN OF COMPUTE AND STORAGE CLOUDS

This section presents basic cloud design principles. We start with basic cloud architecture to process massive amounts of data with a high degree of parallelism. Then we study virtualization support, resource provisioning, infrastructure management, and performance modeling.

4.3.1 A Generic Cloud Architecture Design

An Internet cloud is envisioned as a public cluster of servers provisioned on demand to perform collective web services or distributed applications using data-center resources. In this section, we will discuss cloud design objectives and then present a basic cloud architecture design.

4.3.1.1 Cloud Platform Design Goals

Scalability, virtualization, efficiency, and reliability are four major design goals of a cloud computing platform. Clouds support Web 2.0 applications. Cloud management receives the user request, finds the correct resources, and then calls the provisioning services which invoke the resources in the cloud. The cloud management software needs to support both physical and virtual machines. Security in shared resources and shared access of data centers also pose another design challenge.

The platform needs to establish a very large-scale HPC infrastructure. The hardware and software systems are combined to make it easy and efficient to operate. System scalability can benefit from cluster architecture. If one service takes a lot of processing power, storage capacity, or network traffic, it is simple to add more servers and bandwidth. System reliability can benefit from this architecture. Data can be put into multiple locations. For example, user e-mail can be put in three disks which expand to different geographically separate data centers. In such a situation, even if one of the data centers crashes, the user data is still accessible. The scale of the cloud architecture can be easily expanded by adding more servers and enlarging the network connectivity accordingly.

4.3.1.2 Enabling Technologies for Clouds

The key driving forces behind cloud computing are the ubiquity of broadband and wireless networking, falling storage costs, and progressive improvements in Internet computing software. Cloud users are able to demand more capacity at peak demand, reduce costs, experiment with new services, and remove unneeded capacity, whereas service providers can increase system utilization via multiplexing, virtualization, and dynamic resource provisioning. Clouds are enabled by the progress in hardware, software, and networking technologies summarized in Table 4.3.

Table 4.3 Cloud-Enabling Technologies in Hardware, Software, and Networking

Technology	Requirements and Benefits
Fast platform deployment	Fast, efficient, and flexible deployment of cloud resources to provide dynamic computing environment to users
Virtual clusters on demand	Virtualized cluster of VMs provisioned to satisfy user demand and virtual cluster reconfigured as workload changes
Multitenant techniques	SaaS for distributing software to a large number of users for their simultaneous use and resource sharing if so desired
Massive data processing	Internet search and web services which often require massive data processing, especially to support personalized services
Web-scale communication	Support for e-commerce, distance education, telemedicine, social networking, digital government, and digital entertainment applications
Distributed storage	Large-scale storage of personal records and public archive information which demands distributed storage over the clouds
Licensing and billing services	License management and billing services which greatly benefit all types of cloud services in utility computing

These technologies play instrumental roles in making cloud computing a reality. Most of these technologies are mature today to meet increasing demand. In the hardware area, the rapid progress in multicore CPUs, memory chips, and disk arrays has made it possible to build faster data centers with huge amounts of storage space. Resource virtualization enables rapid cloud deployment and disaster recovery. *Service-oriented architecture* (SOA) also plays a vital role.

Progress in providing SaaS, Web 2.0 standards, and Internet performance have all contributed to the emergence of cloud services. Today's clouds are designed to serve a large number of tenants over massive volumes of data. The availability of large-scale, distributed storage systems is the foundation of today's data centers. Of course, cloud computing is greatly benefitted by the progress made in license management and automatic billing techniques in recent years.

4.3.1.3 A Generic Cloud Architecture

Figure 4.14 shows a security-aware cloud architecture. The Internet cloud is envisioned as a massive cluster of servers. These servers are provisioned on demand to perform collective web services or distributed applications using data-center resources. The cloud platform is formed dynamically by provisioning or deprovisioning servers, software, and database resources. Servers in the cloud can be physical machines or VMs. User interfaces are applied to request services. The provisioning tool carves out the cloud system to deliver the requested service.

In addition to building the server cluster, the cloud platform demands distributed storage and accompanying services. The cloud computing resources are built into the data centers, which are typically owned and operated by a third-party provider. Consumers do not need to know the underlying technologies. In a cloud, software becomes a service. The cloud demands a high degree of trust of massive amounts of data retrieved from large data centers. We need to build a framework to process large-scale data stored in the storage system. This demands a distributed file system over the database system. Other cloud resources are added into a cloud platform, including storage area networks (SANs), database systems, firewalls, and security devices. Web service providers offer

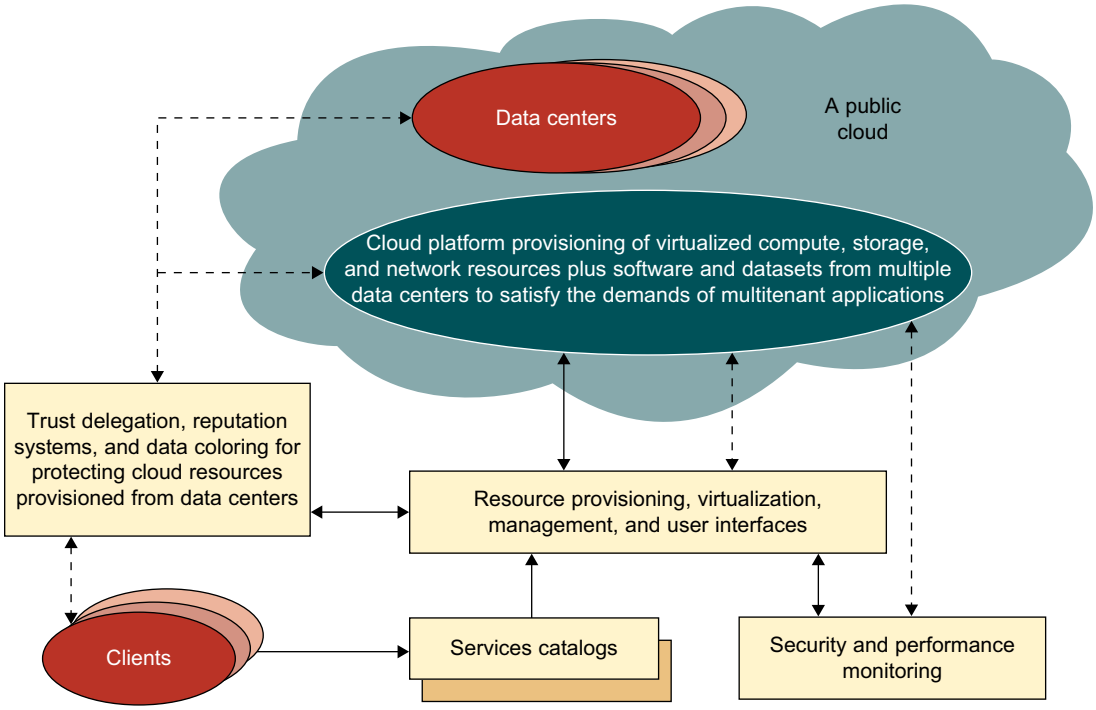


FIGURE 4.14

A security-aware cloud platform built with a virtual cluster of VMs, storage, and networking resources over the data-center servers operated by providers.

(*Courtesy of K. Hwang and D. Li, 2010 [36]*)

special APIs that enable developers to exploit Internet clouds. Monitoring and metering units are used to track the usage and performance of provisioned resources.

The software infrastructure of a cloud platform must handle all resource management and do most of the maintenance automatically. Software must detect the status of each node server joining and leaving, and perform relevant tasks accordingly. Cloud computing providers, such as Google and Microsoft, have built a large number of data centers all over the world. Each data center may have thousands of servers. The location of the data center is chosen to reduce power and cooling costs. Thus, the data centers are often built around hydroelectric power. The cloud physical platform builder is more concerned about the performance/price ratio and reliability issues than shear speed performance.

In general, private clouds are easier to manage, and public clouds are easier to access. The trends in cloud development are that more and more clouds will be hybrid. This is because many cloud applications must go beyond the boundary of an intranet. One must learn how to create a private cloud and how to interact with public clouds in the open Internet. Security becomes a critical issue in safeguarding the operation of all cloud types. We will study cloud security and privacy issues at the end of this chapter.

4.3.2 Layered Cloud Architectural Development

The architecture of a cloud is developed at three layers: infrastructure, platform, and application, as demonstrated in Figure 4.15. These three development layers are implemented with virtualization and standardization of hardware and software resources provisioned in the cloud. The services to public, private, and hybrid clouds are conveyed to users through networking support over the Internet and intranets involved. It is clear that the infrastructure layer is deployed first to support IaaS services. This infrastructure layer serves as the foundation for building the platform layer of the cloud for supporting PaaS services. In turn, the platform layer is a foundation for implementing the application layer for SaaS applications. Different types of cloud services demand application of these resources separately.

The infrastructure layer is built with virtualized compute, storage, and network resources. The abstraction of these hardware resources is meant to provide the flexibility demanded by users. Internally, virtualization realizes automated provisioning of resources and optimizes the infrastructure management process. The platform layer is for general-purpose and repeated usage of the collection of software resources. This layer provides users with an environment to develop their applications, to test operation flows, and to monitor execution results and performance. The platform should be able to assure users that they have scalability, dependability, and security protection. In a way, the virtualized cloud platform serves as a "system middleware" between the infrastructure and application layers of the cloud.

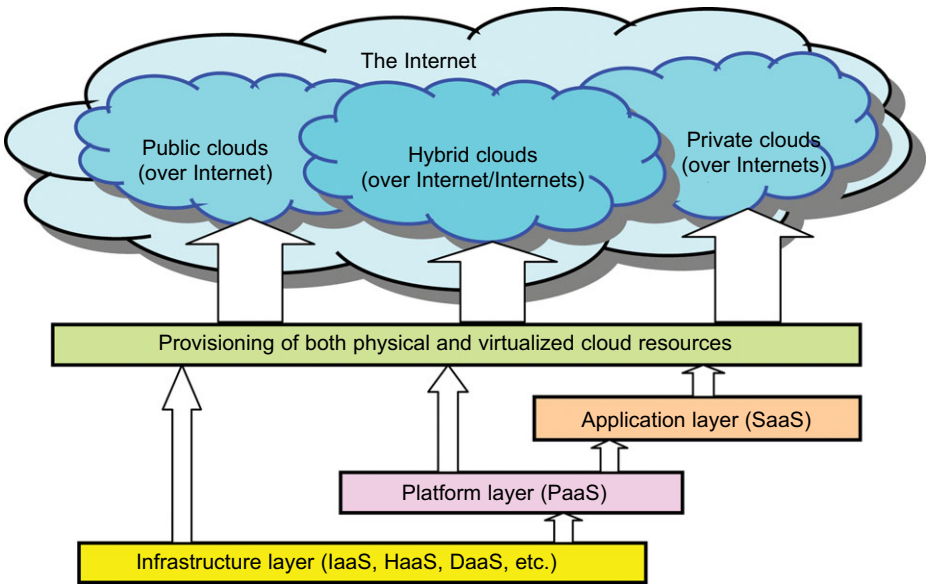


FIGURE 4.15

Layered architectural development of the cloud platform for IaaS, PaaS, and SaaS applications over the Internet.

The application layer is formed with a collection of all needed software modules for SaaS applications. Service applications in this layer include daily office management work, such as information retrieval, document processing, and calendar and authentication services. The application layer is also heavily used by enterprises in business marketing and sales, consumer relationship management (CRM), financial transactions, and supply chain management. It should be noted that not all cloud services are restricted to a single layer. Many applications may apply resources at mixed layers. After all, the three layers are built from the bottom up with a dependence relationship.

From the provider's perspective, the services at various layers demand different amounts of functionality support and resource management by providers. In general, SaaS demands the most work from the provider, PaaS is in the middle, and IaaS demands the least. For example, Amazon EC2 provides not only virtualized CPU resources to users, but also management of these provisioned resources. Services at the application layer demand more work from providers. The best example of this is the Salesforce.com CRM service, in which the provider supplies not only the hardware at the bottom layer and the software at the top layer, but also the platform and software tools for user application development and monitoring.

4.3.2.1 Market-Oriented Cloud Architecture

As consumers rely on cloud providers to meet more of their computing needs, they will require a specific level of QoS to be maintained by their providers, in order to meet their objectives and sustain their operations. Cloud providers consider and meet the different QoS parameters of each individual consumer as negotiated in specific SLAs. To achieve this, the providers cannot deploy traditional system-centric resource management architecture. Instead, market-oriented resource management is necessary to regulate the supply and demand of cloud resources to achieve market equilibrium between supply and demand.

The designer needs to provide feedback on economic incentives for both consumers and providers. The purpose is to promote QoS-based resource allocation mechanisms. In addition, clients can benefit from the potential cost reduction of providers, which could lead to a more competitive market, and thus lower prices. Figure 4.16 shows the high-level architecture for supporting market-oriented resource allocation in a cloud computing environment. This cloud is basically built with the following entities:

Users or brokers acting on user's behalf submit service requests from anywhere in the world to the data center and cloud to be processed. The SLA resource allocator acts as the interface between the data center/cloud service provider and external users/brokers. It requires the interaction of the following mechanisms to support SLA-oriented resource management. When a service request is first submitted the service request examiner interprets the submitted request for QoS requirements before determining whether to accept or reject the request.

The request examiner ensures that there is no overloading of resources whereby many service requests cannot be fulfilled successfully due to limited resources. It also needs the latest status information regarding resource availability (from the VM Monitor mechanism) and workload processing (from the Service Request Monitor mechanism) in order to make resource allocation decisions effectively. Then it assigns requests to VMs and determines resource entitlements for allocated VMs.

The Pricing mechanism decides how service requests are charged. For instance, requests can be charged based on submission time (peak/off-peak), pricing rates (fixed/changing), or availability of

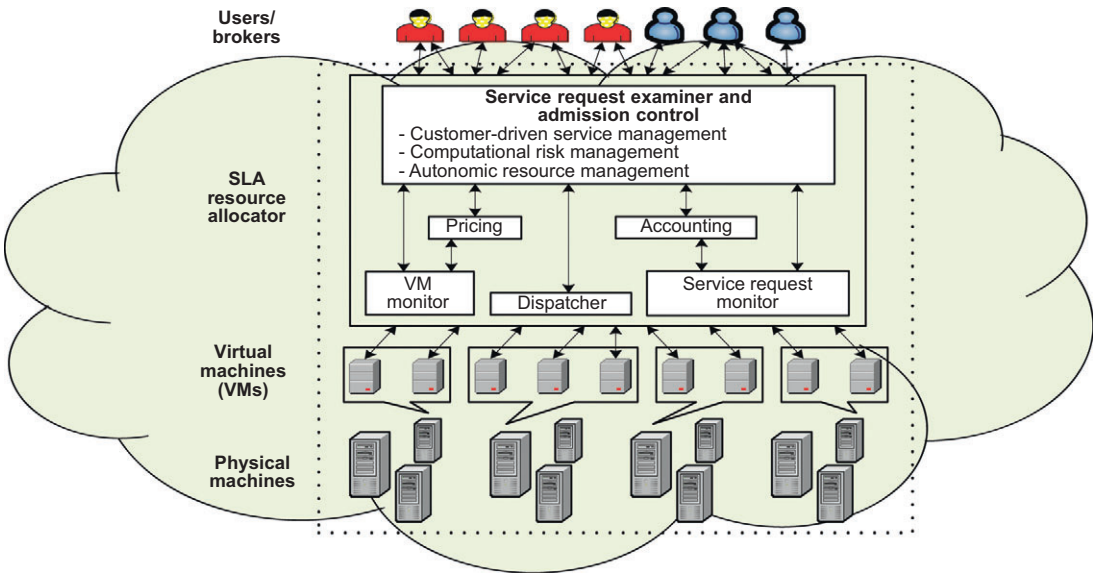


FIGURE 4.16

Market-oriented cloud architecture to expand/shrink leasing of resources with variation in QoS/demand from users. (*Courtesy of Raj Buyya, et al. [11]*)

resources (supply/demand). Pricing serves as a basis for managing the supply and demand of computing resources within the data center and facilitates in prioritizing resource allocations effectively. The Accounting mechanism maintains the actual usage of resources by requests so that the final cost can be computed and charged to users. In addition, the maintained historical usage information can be utilized by the Service Request Examiner and Admission Control mechanism to improve resource allocation decisions.

The VM Monitor mechanism keeps track of the availability of VMs and their resource entitlements. The Dispatcher mechanism starts the execution of accepted service requests on allocated VMs. The Service Request Monitor mechanism keeps track of the execution progress of service requests. Multiple VMs can be started and stopped on demand on a single physical machine to meet accepted service requests, hence providing maximum flexibility to configure various partitions of resources on the same physical machine to different specific requirements of service requests. In addition, multiple VMs can concurrently run applications based on different operating system environments on a single physical machine since the VMs are isolated from one another on the same physical machine.

4.3.2.2 Quality of Service Factors

The data center comprises multiple computing servers that provide resources to meet service demands. In the case of a cloud as a commercial offering to enable crucial business operations of companies, there are critical QoS parameters to consider in a service request, such as time, cost, reliability, and trust/security. In particular, QoS requirements cannot be static and may change over time due to continuing changes in business operations and operating environments. In short, there should

be greater importance on customers since they pay to access services in clouds. In addition, the state of the art in cloud computing has no or limited support for dynamic negotiation of SLAs between participants and mechanisms for automatic allocation of resources to multiple competing requests. Negotiation mechanisms are needed to respond to alternate offers protocol for establishing SLAs [72].

Commercial cloud offerings must be able to support customer-driven service management based on customer profiles and requested service requirements. Commercial clouds define computational risk management tactics to identify, assess, and manage risks involved in the execution of applications with regard to service requirements and customer needs. The cloud also derives appropriate market-based resource management strategies that encompass both customer-driven service management and computational risk management to sustain SLA-oriented resource allocation. The system incorporates autonomic resource management models that effectively self-manage changes in service requirements to satisfy both new service demands and existing service obligations, and leverage VM technology to dynamically assign resource shares according to service requirements.

4.3.3 Virtualization Support and Disaster Recovery

One very distinguishing feature of cloud computing infrastructure is the use of system virtualization and the modification to provisioning tools. Virtualization of servers on a shared cluster can consolidate web services. As the VMs are the containers of cloud services, the provisioning tools will first find the corresponding physical machines and deploy the VMs to those nodes before scheduling the service to run on the virtual nodes.

In addition, in cloud computing, virtualization also means the resources and fundamental infrastructure are virtualized. The user will not care about the computing resources that are used for providing the services. Cloud users do not need to know and have no way to discover physical resources that are involved while processing a service request. Also, application developers do not care about some infrastructure issues such as scalability and fault tolerance (i.e., they are virtualized). Application developers focus on service logic. Figure 4.17 shows the infrastructure needed to virtualize the servers in a data center for implementing specific cloud applications.

4.3.3.1 Hardware Virtualization

In many cloud computing systems, virtualization software is used to virtualize the hardware. System virtualization software is a special kind of software which simulates the execution of hardware and runs even unmodified operating systems. Cloud computing systems use virtualization software as the running environment for legacy software such as old operating systems and unusual applications. Virtualization software is also used as the platform for developing new cloud applications that enable developers to use any operating systems and programming environments they like. The development environment and deployment environment can now be the same, which eliminates some runtime problems.

Some cloud computing providers have used virtualization technology to provide this service for developers. As mentioned before, system virtualization software is considered the hardware analog mechanism to run an unmodified operating system, usually on bare hardware directly, on top of software. Table 4.4 lists some of the system virtualization software in wide use at the time of this writing. Currently, the VMs installed on a cloud computing platform are mainly used for hosting third-party programs. VMs provide flexible runtime services to free users from worrying about the system environment.

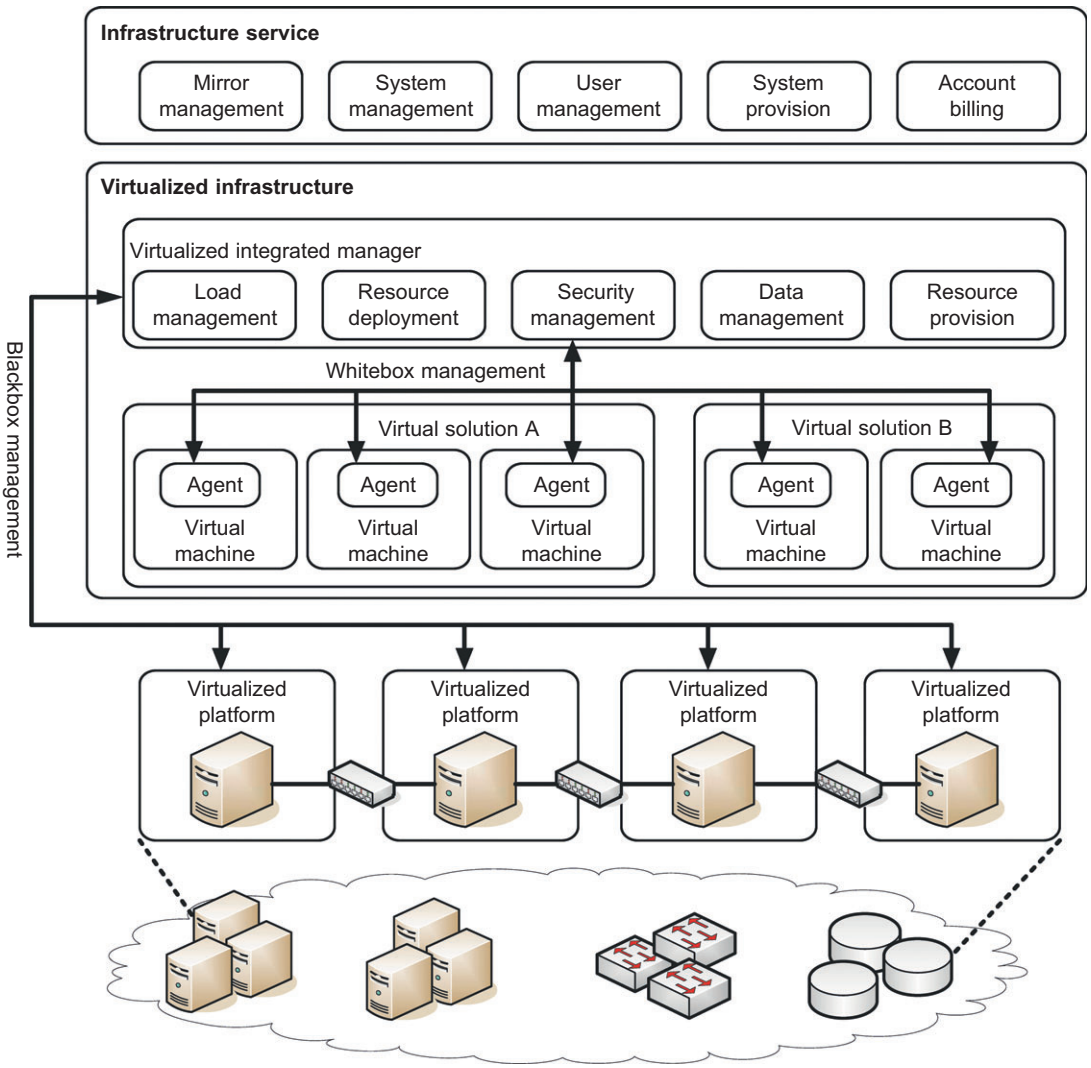


FIGURE 4.17

Virtualized servers, storage, and network for cloud platform construction.

(*Courtesy of Zhong-Yuan Qin, SouthEast University, China*)

Using VMs in a cloud computing platform ensures extreme flexibility for users. As the computing resources are shared by many users, a method is required to maximize the users' privileges and still keep them separated safely. Traditional sharing of cluster resources depends on the user and group mechanism on a system. Such sharing is not flexible. Users cannot customize the system for their special purposes. Operating systems cannot be changed. The separation is not complete.

Table 4.4 Virtualized Resources in Compute, Storage, and Network Clouds [4]

Provider	AWS	Microsoft Azure	GAE
Compute cloud with virtual cluster of servers	x86 instruction set, Xen VMs, resource elasticity allows scalability through virtual cluster, or a third party such as RightScale must provide the cluster	Common language runtime VMs provisioned by declarative descriptions	Predefined application framework handlers written in Python, automatic scaling up and down, server failover inconsistent with the web applications
Storage cloud with virtual storage	Models for block store (EBS) and augmented key/blob store (SimpleDB), automatic scaling varies from EBS to fully automatic (SimpleDB, S3)	SQL Data Services (restricted view of SQL Server), Azure storage service	MegaStore/BigTable
Network cloud services	Declarative IP-level topology; placement details hidden, security groups restricting communication, availability zones isolate network failure, elastic IP applied	Automatic with user's declarative descriptions or roles of app. components	Fixed topology to accommodate three-tier web app. structure, scaling up and down is automatic and programmer-invisible

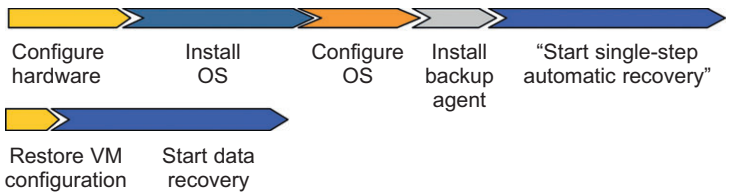


FIGURE 4.18

Recovery overhead of a conventional disaster recovery scheme, compared with that required to recover from live migration of VMs.

An environment that meets one user's requirements often cannot satisfy another user. Virtualization allows users to have full privileges while keeping them separate.

Users have full access to their own VMs, which are completely separate from other users' VMs. Multiple VMs can be mounted on the same physical server. Different VMs may run with different OSes. We also need to establish the virtual disk storage and virtual networks needed by the VMs. The virtualized resources form a resource pool. The virtualization is carried out by special servers dedicated to generating the virtualized resource pool. The virtualized infrastructure (black box in the middle) is built with many *virtualizing integration managers*. These managers handle loads, resources, security, data, and provisioning functions. Figure 4.18 shows two VM platforms. Each platform carries out a virtual solution to a user job. All cloud services are managed in the boxes at the top.

4.3.3.2 Virtualization Support in Public Clouds

Armbrust, et al. [4] have assessed in Table 4.4 three public clouds in the context of virtualization support: AWS, Microsoft Azure, and GAE. AWS provides extreme flexibility (VMs) for users to execute their own applications. GAE provides limited application-level virtualization for users to build applications only based on the services that are created by Google. Microsoft provides programming-level virtualization (.NET virtualization) for users to build their applications.

The VMware tools apply to workstations, servers, and virtual infrastructure. The Microsoft tools are used on PCs and some special servers. The XenEnterprise tool applies only to Xen-based servers. Everyone is interested in the cloud; the entire IT industry is moving toward the vision of the cloud. Virtualization leads to HA, disaster recovery, dynamic load leveling, and rich provisioning support. Both cloud computing and utility computing leverage the benefits of virtualization to provide a scalable and autonomous computing environment.

4.3.3.3 Storage Virtualization for Green Data Centers

IT power consumption in the United States has more than doubled to 3 percent of the total energy consumed in the country. The large number of data centers in the country has contributed to this energy crisis to a great extent. More than half of the companies in the Fortune 500 are actively implementing new corporate energy policies. Recent surveys from both IDC and Gartner confirm the fact that virtualization had a great impact on cost reduction from reduced power consumption in physical computing systems. This alarming situation has made the IT industry become more energy-aware. With little evolution of alternate energy resources, there is an imminent need to conserve power in all computers. Virtualization and server consolidation have already proven handy in this aspect. Green data centers and benefits of storage virtualization are considered to further strengthen the synergy of green computing.

4.3.3.4 Virtualization for IaaS

VM technology has increased in ubiquity. This has enabled users to create customized environments atop physical infrastructure for cloud computing. Use of VMs in clouds has the following distinct benefits: (1) System administrators consolidate workloads of underutilized servers in fewer servers; (2) VMs have the ability to run legacy code without interfering with other APIs; (3) VMs can be used to improve security through creation of sandboxes for running applications with questionable reliability; And (4) virtualized cloud platforms can apply performance isolation, letting providers offer some guarantees and better QoS to customer applications.

4.3.3.5 VM Cloning for Disaster Recovery

VM technology requires an advanced disaster recovery scheme. One scheme is to recover one physical machine by another physical machine. The second scheme is to recover one VM by another VM. As shown in the top timeline of Figure 4.18, traditional disaster recovery from one physical machine to another is rather slow, complex, and expensive. Total recovery time is attributed to the hardware configuration, installing and configuring the OS, installing the backup agents, and the long time to restart the physical machine. To recover a VM platform, the installation and configuration times for the OS and backup agents are eliminated. Therefore, we end up with a much shorter disaster recovery time, about 40 percent of that to recover the physical machines. Virtualization aids in fast disaster recovery by VM encapsulation.

We discussed disaster recovery in Chapters 2 and 3. The cloning of VMs offers an effective solution. The idea is to make a clone VM on a remote server for every running VM on a local server. Among all the clone VMs, only one needs to be active. The remote VM should be in a suspended mode. A cloud control center should be able to activate this clone VM in case of failure of the original VM, taking a snapshot of the VM to enable live migration in a minimal amount of time. The migrated VM can run on a shared Internet connection. Only updated data and modified states are sent to the suspended VM to update its state. The *Recovery Property Objective (RPO)* and *Recovery Time Objective (RTO*) are affected by the number of snapshots taken. Security of the VMs should be enforced during live migration of VMs.

4.3.4 Architectural Design Challenges

In this section, we will identify six open challenges in cloud architecture development. Armbrust, et al. [4] have observed some of these topics as both obstacles and opportunities. Plausible solutions to meet these challenges are discussed shortly.

4.3.4.1 Challenge 1—Service Availability and Data Lock-in Problem

The management of a cloud service by a single company is often the source of single points of failure. To achieve HA, one can consider using multiple cloud providers. Even if a company has multiple data centers located in different geographic regions, it may have common software infrastructure and accounting systems. Therefore, using multiple cloud providers may provide more protection from failures. Another availability obstacle is distributed *denial of service* (DDoS) attacks. Criminals threaten to cut off the incomes of SaaS providers by making their services unavailable. Some utility computing services offer SaaS providers the opportunity to defend against DDoS attacks by using quick scale-ups.

Software stacks have improved interoperability among different cloud platforms, but the APIs itself are still proprietary. Thus, customers cannot easily extract their data and programs from one site to run on another. The obvious solution is to standardize the APIs so that a SaaS developer can deploy services and data across multiple cloud providers. This will rescue the loss of all data due to the failure of a single company. In addition to mitigating data lock-in concerns, standardization of APIs enables a new usage model in which the same software infrastructure can be used in both public and private clouds. Such an option could enable "surge computing," in which the public cloud is used to capture the extra tasks that cannot be easily run in the data center of a private cloud.

4.3.4.2 Challenge 2—Data Privacy and Security Concerns

Current cloud offerings are essentially public (rather than private) networks, exposing the system to more attacks. Many obstacles can be overcome immediately with well-understood technologies such as encrypted storage, virtual LANs, and network middleboxes (e.g., firewalls, packet filters). For example, you could encrypt your data before placing it in a cloud. Many nations have laws requiring SaaS providers to keep customer data and copyrighted material within national boundaries.

Traditional network attacks include buffer overflows, DoS attacks, spyware, malware, rootkits, Trojan horses, and worms. In a cloud environment, newer attacks may result from hypervisor malware, guest hopping and hijacking, or VM rootkits. Another type of attack is the man-in-the-middle

attack for VM migrations. In general, passive attacks steal sensitive data or passwords. Active attacks may manipulate kernel data structures which will cause major damage to cloud servers. We will study all of these security and privacy problems on clouds in Section 4.5.

4.3.4.3 Challenge 3—Unpredictable Performance and Bottlenecks

Multiple VMs can share CPUs and main memory in cloud computing, but I/O sharing is problematic. For example, to run 75 EC2 instances with the STREAM benchmark requires a mean bandwidth of 1,355 MB/second. However, for each of the 75 EC2 instances to write 1 GB files to the local disk requires a mean disk write bandwidth of only 55 MB/second. This demonstrates the problem of I/O interference between VMs. One solution is to improve I/O architectures and operating systems to efficiently virtualize interrupts and I/O channels.

Internet applications continue to become more data-intensive. If we assume applications to be "pulled apart" across the boundaries of clouds, this may complicate data placement and transport. Cloud users and providers have to think about the implications of placement and traffic at every level of the system, if they want to minimize costs. This kind of reasoning can be seen in Amazon's development of its new CloudFront service. Therefore, data transfer bottlenecks must be removed, bottleneck links must be widened, and weak servers should be removed. We will study performance issues in Chapter 8.

4.3.4.4 Challenge 4—Distributed Storage and Widespread Software Bugs

The database is always growing in cloud applications. The opportunity is to create a storage system that will not only meet this growth, but also combine it with the cloud advantage of scaling arbitrarily up and down on demand. This demands the design of efficient distributed SANs. Data centers must meet programmers' expectations in terms of scalability, data durability, and HA. Data consistence checking in SAN-connected data centers is a major challenge in cloud computing.

Large-scale distributed bugs cannot be reproduced, so the debugging must occur at a scale in the production data centers. No data center will provide such a convenience. One solution may be a reliance on using VMs in cloud computing. The level of virtualization may make it possible to capture valuable information in ways that are impossible without using VMs. Debugging over simulators is another approach to attacking the problem, if the simulator is well designed.

4.3.4.5 Challenge 5—Cloud Scalability, Interoperability, and Standardization

The pay-as-you-go model applies to storage and network bandwidth; both are counted in terms of the number of bytes used. Computation is different depending on virtualization level. GAE automatically scales in response to load increases and decreases; users are charged by the cycles used. AWS charges by the hour for the number of VM instances used, even if the machine is idle. The opportunity here is to scale quickly up and down in response to load variation, in order to save money, but without violating SLAs.

Open Virtualization Format (OVF) describes an open, secure, portable, efficient, and extensible format for the packaging and distribution of VMs. It also defines a format for distributing software to be deployed in VMs. This VM format does not rely on the use of a specific host platform, virtualization platform, or guest operating system. The approach is to address virtual platform-agnostic packaging with certification and integrity of packaged software. The package supports virtual appliances to span more than one VM.

OVF also defines a transport mechanism for VM templates, and can apply to different virtualization platforms with different levels of virtualization. In terms of cloud standardization, we suggest the ability for virtual appliances to run on any virtual platform. We also need to enable VMs to run on heterogeneous hardware platform hypervisors. This requires hypervisor-agnostic VMs. We also need to realize cross-platform live migration between x86 Intel and AMD technologies and support legacy hardware for load balancing. All these issue are wide open for further research.

4.3.4.6 Challenge 6—Software Licensing and Reputation Sharing

Many cloud computing providers originally relied on open source software because the licensing model for commercial software is not ideal for utility computing. The primary opportunity is either for open source to remain popular or simply for commercial software companies to change their licensing structure to better fit cloud computing. One can consider using both pay-for-use and bulk-use licensing schemes to widen the business coverage.

One customer's bad behavior can affect the reputation of the entire cloud. For instance, blacklisting of EC2 IP addresses by spam-prevention services may limit smooth VM installation. An opportunity would be to create reputation-guarding services similar to the "trusted e-mail" services currently offered (for a fee) to services hosted on smaller ISPs. Another legal issue concerns the transfer of legal liability. Cloud providers want legal liability to remain with the customer, and vice versa. This problem must be solved at the SLA level. We will study reputation systems for protecting data centers in the next section.

4.4 PUBLIC CLOUD PLATFORMS: GAE, AWS, AND AZURE

In this section, we will review the system architectures of four commercially available cloud platforms. These case studies will prepare readers for subsequent sections and chapters.

4.4.1 Public Clouds and Service Offerings

Cloud services are demanded by computing and IT administrators, software vendors, and end users. Figure 4.19 introduces five levels of cloud players. At the top level, individual users and organizational users demand very different services. The application providers at the SaaS level serve mainly individual users. Most business organizations are serviced by IaaS and PaaS providers. The infrastructure services (IaaS) provide compute, storage, and communication resources to both applications and organizational users. The cloud environment is defined by the PaaS or platform providers. Note that the platform providers support both infrastructure services and organizational users directly.

Cloud services rely on new advances in machine virtualization, SOA, grid infrastructure management, and power efficiency. Consumers purchase such services in the form of IaaS, PaaS, or SaaS as described earlier. Also, many cloud entrepreneurs are selling value-added utility services to massive numbers of users. The cloud industry leverages the growing demand by many enterprises and business users to outsource their computing and storage jobs to professional providers. The provider service charges are often much lower than the cost for users to replace their obsolete servers frequently. Table 4.5 summarizes the profiles of five major cloud providers by 2010 standards.

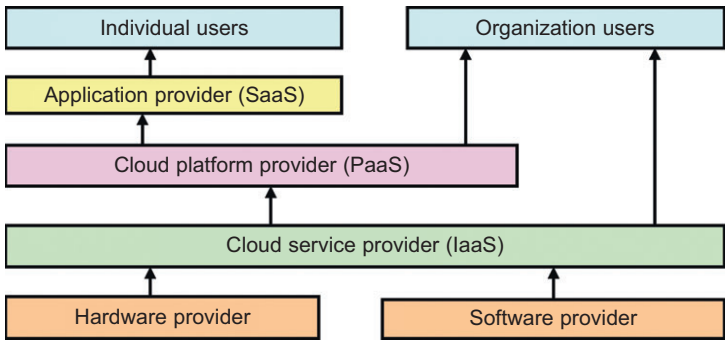


FIGURE 4.19

Roles of individual and organizational users and their interaction with cloud providers under various cloud service models.

Table 4.5 Five Major Cloud Platforms and Their Service Offerings [36]

Model	IBM	Amazon	Google	Microsoft	Salesforce
PaaS	BlueCloud, WCA, RC2		App Engine (GAE)	Windows Azure	Force.com
IaaS	Ensembles	AWS		Windows Azure	
SaaS	Lotus Live		Gmail, Docs	.NET service, Dynamic CRM	Online CRM, Gifttag
Virtualization		OS and Xen	Application Container	OS level/ Hypel-V	
Service Offerings	SOA, B2, TSAM, RAD, Web 2.0	EC2, S3, SQS, SimpleDB	GFS, Chubby, BigTable, MapReduce	Live, SQL Hotmail	Apex, visual force, record security
Security Features	WebSphere2 and PowerVM tuned for protection	PKI, VPN, EBS to recover from failure	Chubby locks for security enforcement	Replicated data, rule-based access control	Admin./record security, uses metadata API
User Interfaces		EC2 command-line tools	Web-based admin. console	Windows Azure portal	
Web API	Yes	Yes	Yes	Yes	Yes
Programming Support	AMI		Python	.NET Framework	

Note: *WCA: WebSphere CloudBurst Appliance; RC2: Research Compute Cloud; RAD: Rational Application Developer; SOA: Service-Oriented Architecture; TSAM: Tivoli Service Automation Manager; EC2: Elastic Compute Cloud; S3: Simple Storage Service; SQS: Simple Queue Service; GAE: Google App Engine; AWS: Amazon Web Services; SQL: Structured Query Language; EBS: Elastic Block Store; CRM: Consumer Relationship Management.*

Amazon pioneered the IaaS business in supporting e-commerce and cloud applications by millions of customers simultaneously. The elasticity in the Amazon cloud comes from the flexibility provided by the hardware and software services. EC2 provides an environment for running virtual servers on demand. S3 provides unlimited online storage space. Both EC2 and S3 are supported in the AWS platform. Microsoft offers the Azure platform for cloud applications. It has also supported the .NET service, dynamic CRM, Hotmail, and SQL applications. Salsforce.com offers extensive SaaS applications for online CRM applications using its Force.com platforms.

As Table 4.5 shows, all IaaS, PaaS, and SaaS models allow users to access services over the Internet, relying entirely on the infrastructures of the cloud service providers. These models are offered based on various SLAs between the providers and the users. SLAs are more common in network services as they account for the QoS characteristics of network services. For cloud computing services, it is difficult to find a reasonable precedent for negotiating an SLA. In a broader sense, the SLAs for cloud computing address service availability, data integrity, privacy, and security protection. Blank spaces in the table refer to unknown or underdeveloped features.

4.4.2 Google App Engine (GAE)

Google has the world's largest search engine facilities. The company has extensive experience in massive data processing that has led to new insights into data-center design (see Chapter 3) and novel programming models that scale to incredible sizes. The Google platform is based on its search engine expertise, but as discussed earlier with MapReduce, this infrastructure is applicable to many other areas. Google has hundreds of data centers and has installed more than 460,000 servers worldwide. For example, 200 Google data centers are used at one time for a number of cloud applications. Data items are stored in text, images, and video and are replicated to tolerate faults or failures. Here we discuss Google's App Engine (GAE) which offers a PaaS platform supporting various cloud and web applications.

4.4.2.1 Google Cloud Infrastructure

Google has pioneered cloud development by leveraging the large number of data centers it operates. For example, Google pioneered cloud services in Gmail, Google Docs, and Google Earth, among other applications. These applications can support a large number of users simultaneously with HA. Notable technology achievements include the Google File System (GFS), MapReduce, BigTable, and Chubby. In 2008, Google announced the GAE web application platform which is becoming a common platform for many small cloud service providers. This platform specializes in supporting scalable (elastic) web applications. GAE enables users to run their applications on a large number of data centers associated with Google's search engine operations.

4.4.2.2 GAE Architecture

Figure 4.20 shows the major building blocks of the Google cloud platform which has been used to deliver the cloud services highlighted earlier. GFS is used for storing large amounts of data. MapReduce is for use in application program development. Chubby is used for distributed application lock services. BigTable offers a storage service for accessing structured data. These technologies are described in more detail in Chapter 8. Users can interact with Google applications via the

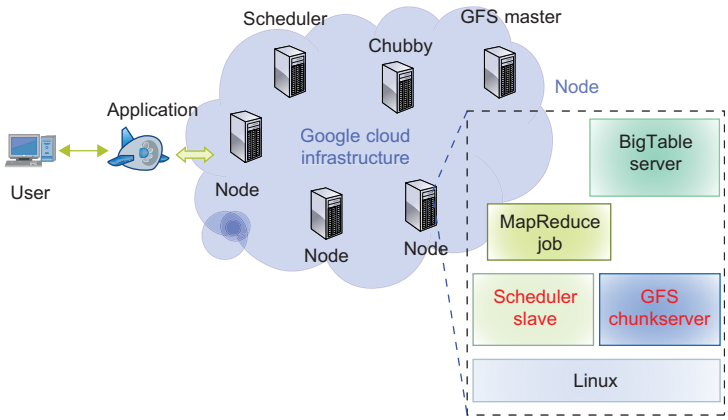


FIGURE 4.20

Google cloud platform and major building blocks, the blocks shown are large clusters of low-cost servers.

(*Courtesy of Kang Chen, Tsinghua University, China*)

web interface provided by each application. Third-party application providers can use GAE to build cloud applications for providing services. The applications all run in data centers under tight management by Google engineers. Inside each data center, there are thousands of servers forming different clusters.

Google is one of the larger cloud application providers, although its fundamental service program is private and outside people cannot use the Google infrastructure to build their own service. The building blocks of Google's cloud computing application include the Google File System for storing large amounts of data, the MapReduce programming framework for application developers, Chubby for distributed application lock services, and BigTable as a storage service for accessing structural or semistructural data. With these building blocks, Google has built many cloud applications. Figure 4.20 shows the overall architecture of the Google cloud infrastructure. A typical cluster configuration can run the Google File System, MapReduce jobs, and BigTable servers for structure data. Extra services such as Chubby for distributed locks can also run in the clusters.

GAE runs the user program on Google's infrastructure. As it is a platform running third-party programs, application developers now do not need to worry about the maintenance of servers. GAE can be thought of as the combination of several software components. The frontend is an application framework which is similar to other web application frameworks such as ASP, J2EE, and JSP. At the time of this writing, GAE supports Python and Java programming environments. The applications can run similar to web application containers. The frontend can be used as the dynamic web serving infrastructure which can provide the full support of common technologies.

4.4.2.3 Functional Modules of GAE

The GAE platform comprises the following five major components. The GAE is not an infrastructure platform, but rather an application development platform for users. We describe the component functionalities separately.

a. The *datastore* offers object-oriented, distributed, structured data storage services based on BigTable techniques. The datastore secures data management operations.
b. The *application runtime environment* offers a platform for scalable web programming and execution. It supports two development languages: Python and Java.
c. The *software development kit* (SDK) is used for local application development. The SDK allows users to execute test runs of local applications and upload application code.
d. The *administration console* is used for easy management of user application development cycles, instead of for physical resource management.
e. The *GAE web service infrastructure* provides special interfaces to guarantee flexible use and management of storage and network resources by GAE.

Google offers essentially free GAE services to all Gmail account owners. You can register for a GAE account or use your Gmail account name to sign up for the service. The service is free within a quota. If you exceed the quota, the page instructs you on how to pay for the service. Then you download the SDK and read the Python or Java guide to get started. Note that GAE only accepts Python, Ruby, and Java programming languages. The platform does not provide any IaaS services, unlike Amazon, which offers Iaas and PaaS. This model allows the user to deploy user-built applications on top of the cloud infrastructure that are built using the programming languages and software tools supported by the provider (e.g., Java, Python). Azure does this similarly for .NET. The user does not manage the underlying cloud infrastructure. The cloud provider facilitates support of application development, testing, and operation support on a well-defined service platform.

4.4.2.4 GAE Applications

Well-known GAE applications include the Google Search Engine, Google Docs, Google Earth, and Gmail. These applications can support large numbers of users simultaneously. Users can interact with Google applications via the web interface provided by each application. Third-party application providers can use GAE to build cloud applications for providing services. The applications are all run in the Google data centers. Inside each data center, there might be thousands of server nodes to form different clusters. (See the previous section.) Each cluster can run multipurpose servers.

GAE supports many web applications. One is a storage service to store application-specific data in the Google infrastructure. The data can be persistently stored in the backend storage server while still providing the facility for queries, sorting, and even transactions similar to traditional database systems. GAE also provides Google-specific services, such as the Gmail account service (which is the login service, that is, applications can use the Gmail account directly). This can eliminate the tedious work of building customized user management components in web applications. Thus, web applications built on top of GAE can use the APIs authenticating users and sending e-mail using Google accounts.

4.4.3 Amazon Web Services (AWS)

VMs can be used to share computing resources both flexibly and safely. Amazon has been a leader in providing public cloud services (http://aws.amazon.com/). Amazon applies the IaaS model in providing its services. Figure 4.21 shows the AWS architecture. EC2 provides the virtualized platforms to the host VMs where the cloud application can run. S3 (Simple Storage Service) provides the object-oriented storage service for users. EBS (Elastic Block Service) provides the block storage

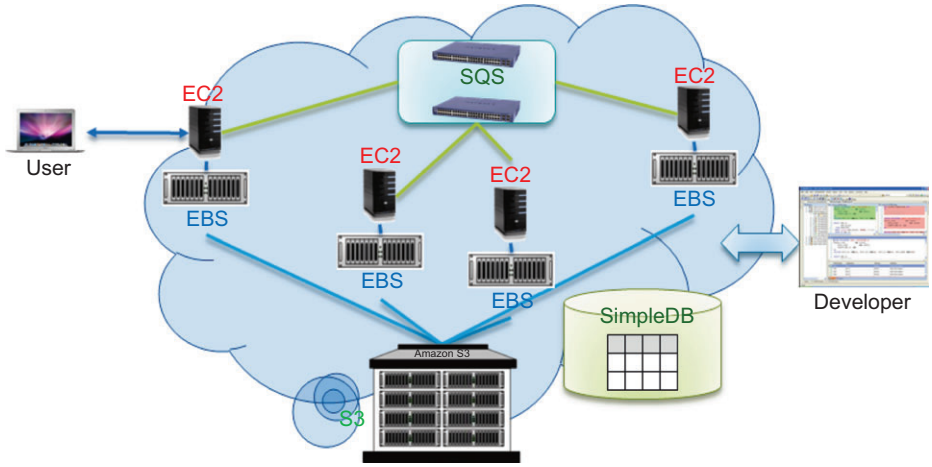


FIGURE 4.21

Amazon cloud computing infrastructure (Key services are identified here; many more are listed in Table 4.6).
(*Courtesy of Kang Chen, Tsinghua University, China*)

interface which can be used to support traditional applications. SQS stands for Simple Queue Service, and its job is to ensure a reliable message service between two processes. The message can be kept reliably even when the receiver processes are not running. Users can access their objects through SOAP with either browsers or other client programs which support the SOAP standard.

Table 4.6 summarizes the service offerings by AWS in 12 application tracks. Details of EC2, S3, and EBS are available in Chapter 6 where we discuss programming examples. Amazon offers queuing and notification services (SQS and SNS), which are implemented in the AWS cloud. Note brokering systems run very efficiently in clouds and offer a striking model for controlling sensors and providing office support of smartphones and tablets. Different from Google, Amazon provides a more flexible cloud computing platform for developers to build cloud applications. Small and medium-size companies can put their business on the Amazon cloud platform. Using the AWS platform, they can service large numbers of Internet users and make profits through those paid services.

ELB automatically distributes incoming application traffic across multiple Amazon EC2 instances and allows user to avoid nonoperating nodes and to equalize load on functioning images. Both autoscaling and ELB are enabled by CloudWatch which monitors running instances. CloudWatch is a web service that provides monitoring for AWS cloud resources, starting with Amazon EC2. It provides customers with visibility into resource utilization, operational performance, and overall demand patterns, including metrics such as CPU utilization, disk reads and writes, and network traffic.

Amazon (like Azure) offers a *Relational Database Service (RDS)* with a messaging interface to be covered in Section 4.1. The Elastic MapReduce capability is equivalent to Hadoop running on the basic EC2 offering. AWS Import/Export allows one to ship large volumes of data to and from EC2 by shipping physical disks; it is well known that this is often the highest bandwidth connection between geographically distant systems. Amazon CloudFront implements a content distribution

Table 4.6 AWS Offerings in 2011

Service Area	Service Modules and Abbreviated Names
Compute	Elastic Compute Cloud (EC2), Elastic MapReduce, Auto Scaling
Messaging	Simple Queue Service (SQS), Simple Notification Service (SNS)
Storage	Simple Storage Service (S3), Elastic Block Storage (EBS), AWS Import/Export
Content Delivery	Amazon CloudFront
Monitoring	Amazon CloudWatch
Support	AWS Premium Support
Database	Amazon SimpleDB, Relational Database Service (RDS)
Networking	Virtual Private Cloud (VPC) (Example 4.1, Figure 4.6), Elastic Load Balancing
Web Traffic	Alexa Web Information Service, Alexa Web Sites
E-Commerce	Fulfillment Web Service (FWS)
Payments and Billing	Flexible Payments Service (FPS), Amazon DevPay
Workforce	Amazon Mechanical Turk

(*Courtesy of Amazon, http://aws.amazon.com [3]*)

network. Amazon DevPay is a simple-to-use online billing and account management service that makes it easy for businesses to sell applications that are built into or run on top of AWS.

FPS provides developers of commercial systems on AWS with a convenient way to charge Amazon's customers that use such services built on AWS. Customers can pay using the same login credentials, shipping address, and payment information they already have on file with Amazon. The FWS allows merchants to access Amazon's fulfillment capabilities through a simple web service interface. Merchants can send order information to Amazon to fulfill customer orders on their behalf. In July 2010, Amazon offered MPI clusters and cluster compute instances. The AWS cluster compute instances use hardware-assisted virtualization instead of the para-virtualization used by other instance types and requires booting from the EBS. Users are freed to create a new AMI as needed.

4.4.4 Microsoft Windows Azure

In 2008, Microsoft launched a Windows Azure platform to meet the challenges in cloud computing. This platform is built over Microsoft data centers. Figure 4.22 shows the overall architecture of Microsoft's cloud platform. The platform is divided into three major component platforms. Windows Azure offers a cloud platform built on Windows OS and based on Microsoft virtualization technology. Applications are installed on VMs deployed on the data-center servers. Azure manages all servers, storage, and network resources of the data center. On top of the infrastructure are the various services for building different cloud applications. Cloud-level services provided by the Azure platform are introduced below. More details on Azure services are given in Chapter 6.

- **Live service** Users can visit Microsoft Live applications and apply the data involved across multiple machines concurrently.
- **.NET service** This package supports application development on local hosts and execution on cloud machines.

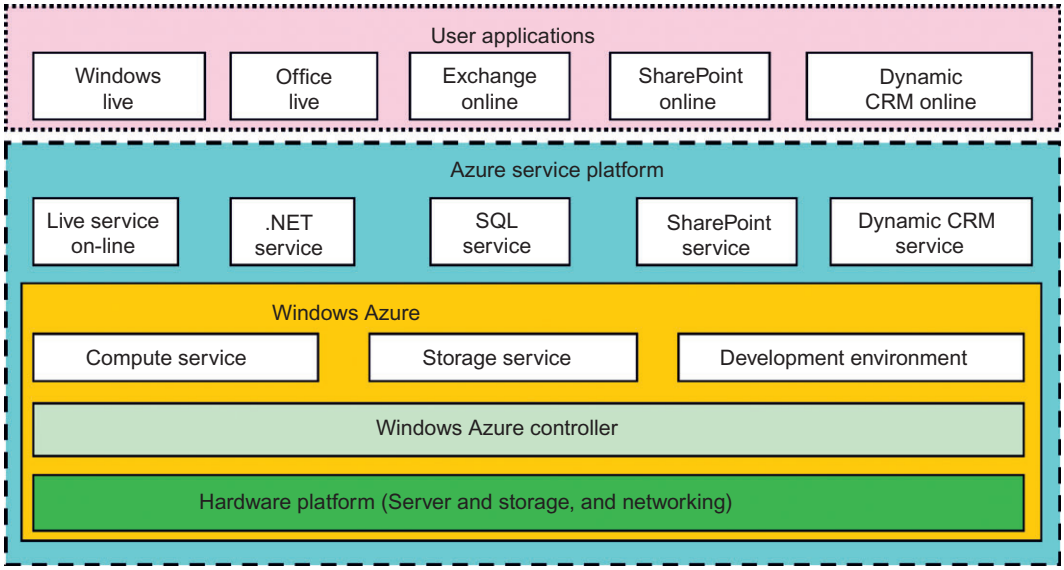


FIGURE 4.22

Microsoft Windows Azure platform for cloud computing.

(*Courtesy of Microsoft, 2010, http://www.microsoft.com/windowsazure*)

- **SQL Azure** This function makes it easier for users to visit and use the relational database associated with the SQL server in the cloud.
- **SharePoint service** This provides a scalable and manageable platform for users to develop their special business applications in upgraded web services.
- **Dynamic CRM service** This provides software developers a business platform in managing CRM applications in financing, marketing, and sales and promotions.

All these cloud services in Azure can interact with traditional Microsoft software applications, such as Windows Live, Office Live, Exchange online, SharePoint online, and dynamic CRM online. The Azure platform applies the standard web communication protocols SOAP and REST. The Azure service applications allow users to integrate the cloud application with other platforms or third-party clouds. You can download the Azure development kit to run a local version of Azure. The powerful SDK allows Azure applications to be developed and debugged on the Windows hosts.

4.5 INTER-CLOUD RESOURCE MANAGEMENT

This section characterizes the various cloud service models and their extensions. The cloud service trends are outlined. Cloud resource management and intercloud resource exchange schemes are reviewed. We will discuss the defense of cloud resources against network threats in Section 4.6.

4.5.1 Extended Cloud Computing Services

Figure 4.23 shows six layers of cloud services, ranging from hardware, network, and collocation to infrastructure, platform, and software applications. We already introduced the top three service layers as SaaS, PaaS, and IaaS, respectively. The cloud platform provides PaaS, which sits on top of the IaaS infrastructure. The top layer offers SaaS. These must be implemented on the cloud platforms provided. Although the three basic models are dissimilar in usage, as shown in Table 4.7, they are built one on top of another. The implication is that one cannot launch SaaS applications with a cloud platform. The cloud platform cannot be built if compute and storage infrastructures are not there.

The bottom three layers are more related to physical requirements. The bottommost layer provides *Hardware as a Service (HaaS)*. The next layer is for interconnecting all the hardware components, and is simply called *Network as a Service (NaaS)*. *Virtual LANs* fall within the scope of NaaS. The next layer up offers *Location as a Service (LaaS)*, which provides a collocation service to house, power, and secure all the physical hardware and network resources. Some authors say this layer provides *Security as a Service* ("SaaS"). The cloud infrastructure layer can be further subdivided as *Data as a Service (DaaS)* and *Communication as a Service (CaaS)* in addition to compute and storage in IaaS.

We will examine commercial trends in cloud services in subsequent sections. Here we will mainly cover the top three layers with some success stories of cloud computing. As shown in Table 4.7, cloud players are divided into three classes: (1) cloud service providers and IT administrators, (2) software developers or vendors, and (3) end users or business users. These cloud players vary in their roles under the IaaS, PaaS, and SaaS models. The table entries distinguish the three cloud models as viewed by different players. From the software vendors' perspective, application performance on a given cloud platform is most important. From the providers' perspective, cloud infrastructure

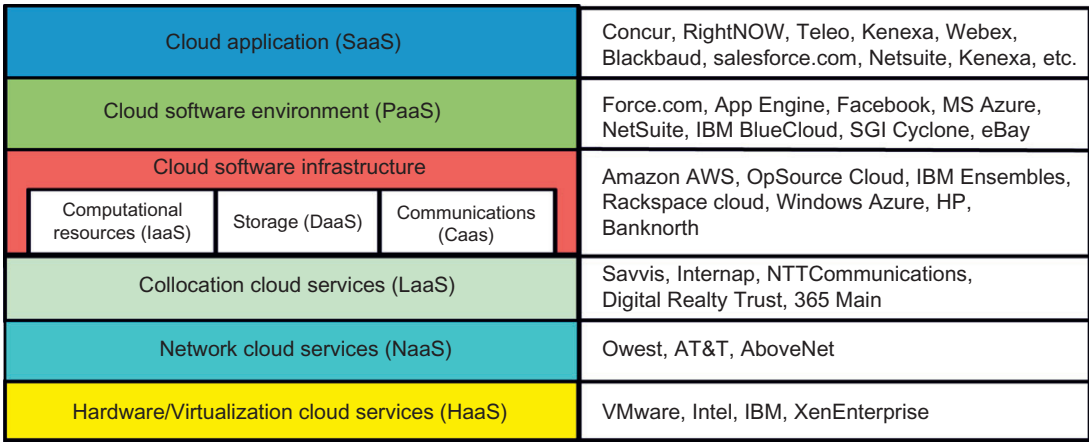


FIGURE 4.23

A stack of six layers of cloud services and their providers.

(*Courtesy of T. Chou, Active Book Express, 2010 [16]*)

Table 4.7 Cloud Differences in Perspectives of Providers, Vendors, and Users

Cloud Players	IaaS	PaaS	SaaS
IT administrators/cloud providers	Monitor SLAs	Monitor SLAs and enable service platforms	Monitor SLAs and deploy software
Software developers (vendors)	To deploy and store data	Enabling platforms via configurators and APIs	Develop and deploy software
End users or business users	To deploy and store data	To develop and test web software	Use business software

performance is the primary concern. From the end users' perspective, the quality of services, including security, is the most important.

4.5.1.1 Cloud Service Tasks and Trends

Cloud services are introduced in five layers. The top layer is for SaaS applications, as further subdivided into the five application areas in Figure 4.23, mostly for business applications. For example, CRM is heavily practiced in business promotion, direct sales, and marketing services. CRM offered the first SaaS on the cloud successfully. The approach is to widen market coverage by investigating customer behaviors and revealing opportunities by statistical analysis. SaaS tools also apply to distributed collaboration, and financial and human resources management. These cloud services have been growing rapidly in recent years.

PaaS is provided by Google, Salesforce.com, and Facebook, among others. IaaS is provided by Amazon, Windows Azure, and RackRack, among others. Collocation services require multiple cloud providers to work together to support supply chains in manufacturing. Network cloud services provide communications such as those by AT&T, Qwest, and AboveNet. Details can be found in Clou's introductory book on business clouds [18]. The vertical cloud services in Figure 4.25 refer to a sequence of cloud services that are mutually supportive. Often, cloud mashup is practiced in vertical cloud applications.

4.5.1.2 Software Stack for Cloud Computing

Despite the various types of nodes in the cloud computing cluster, the overall software stacks are built from scratch to meet rigorous goals (see Table 4.7). Developers have to consider how to design the system to meet critical requirements such as high throughput, HA, and fault tolerance. Even the operating system might be modified to meet the special requirement of cloud data processing. Based on the observations of some typical cloud computing instances, such as Google, Microsoft, and Yahoo!, the overall software stack structure of cloud computing software can be viewed as layers. Each layer has its own purpose and provides the interface for the upper layers just as the traditional software stack does. However, the lower layers are not completely transparent to the upper layers.

The platform for running cloud computing services can be either physical servers or virtual servers. By using VMs, the platform can be flexible, that is, the running services are not bound to specific hardware platforms. This brings flexibility to cloud computing platforms. The software layer on top of the platform is the layer for storing massive amounts of data. This layer acts like

the file system in a traditional single machine. Other layers running on top of the file system are the layers for executing cloud computing applications. They include the database storage system, programming for large-scale clusters, and data query language support. The next layers are the components in the software stack.

4.5.1.3 Runtime Support Services

As in a cluster environment, there are also some runtime supporting services in the cloud computing environment. Cluster monitoring is used to collect the runtime status of the entire cluster. One of the most important facilities is the cluster job management system introduced in Chapter 2. The scheduler queues the tasks submitted to the whole cluster and assigns the tasks to the processing nodes according to node availability. The distributed scheduler for the cloud application has special characteristics that can support cloud applications, such as scheduling the programs written in MapReduce style. The runtime support system keeps the cloud cluster working properly with high efficiency.

Runtime support is software needed in browser-initiated applications applied by thousands of cloud customers. The SaaS model provides the software applications as a service, rather than letting users purchase the software. As a result, on the customer side, there is no upfront investment in servers or software licensing. On the provider side, costs are rather low, compared with conventional hosting of user applications. The customer data is stored in the cloud that is either vendor proprietary or a publicly hosted cloud supporting PaaS and IaaS.

4.5.2 Resource Provisioning and Platform Deployment

The emergence of computing clouds suggests fundamental changes in software and hardware architecture. Cloud architecture puts more emphasis on the number of processor cores or VM instances. Parallelism is exploited at the cluster node level. In this section, we will discuss techniques to provision computer resources or VMs. Then we will talk about storage allocation schemes to interconnect distributed computing infrastructures by harnessing the VMs dynamically.

4.5.2.1 Provisioning of Compute Resources (VMs)

Providers supply cloud services by signing SLAs with end users. The SLAs must commit sufficient resources such as CPU, memory, and bandwidth that the user can use for a preset period. Underprovisioning of resources will lead to broken SLAs and penalties. Overprovisioning of resources will lead to resource underutilization, and consequently, a decrease in revenue for the provider. Deploying an autonomous system to efficiently provision resources to users is a challenging problem. The difficulty comes from the unpredictability of consumer demand, software and hardware failures, heterogeneity of services, power management, and conflicts in signed SLAs between consumers and service providers.

Efficient VM provisioning depends on the cloud architecture and management of cloud infrastructures. Resource provisioning schemes also demand fast discovery of services and data in cloud computing infrastructures. In a virtualized cluster of servers, this demands efficient installation of VMs, live VM migration, and fast recovery from failures. To deploy VMs, users treat them as physical hosts with customized operating systems for specific applications. For example, Amazon's EC2 uses Xen as the virtual machine monitor (VMM). The same VMM is used in IBM's Blue Cloud.

In the EC2 platform, some predefined VM templates are also provided. Users can choose different kinds of VMs from the templates. IBM's Blue Cloud does not provide any VM templates. In general, any type of VM can run on top of Xen. Microsoft also applies virtualization in its Azure cloud platform. The provider should offer resource-economic services. Power-efficient schemes for caching, query processing, and thermal management are mandatory due to increasing energy waste by heat dissipation from data centers. Public or private clouds promise to streamline the on-demand provisioning of software, hardware, and data as a service, achieving economies of scale in IT deployment and operation.

4.5.2.2 Resource Provisioning Methods

Figure 4.24 shows three cases of static cloud resource provisioning policies. In case (a), overprovisioning with the peak load causes heavy resource waste (shaded area). In case (b), underprovisioning (along the capacity line) of resources results in losses by both user and provider in that paid demand by the users (the shaded area above the capacity) is not served and wasted resources still exist for those demanded areas below the provisioned capacity. In case (c), the constant provisioning of resources with fixed capacity to a declining user demand could result in even worse resource waste. The user may give up the service by canceling the demand, resulting in reduced revenue for the provider. Both the user and provider may be losers in resource provisioning without elasticity.

Three resource-provisioning methods are presented in the following sections. The *demand-driven method* provides static resources and has been used in grid computing for many years. The *event-driven method* is based on predicted workload by time. The *popularity-driven method* is based

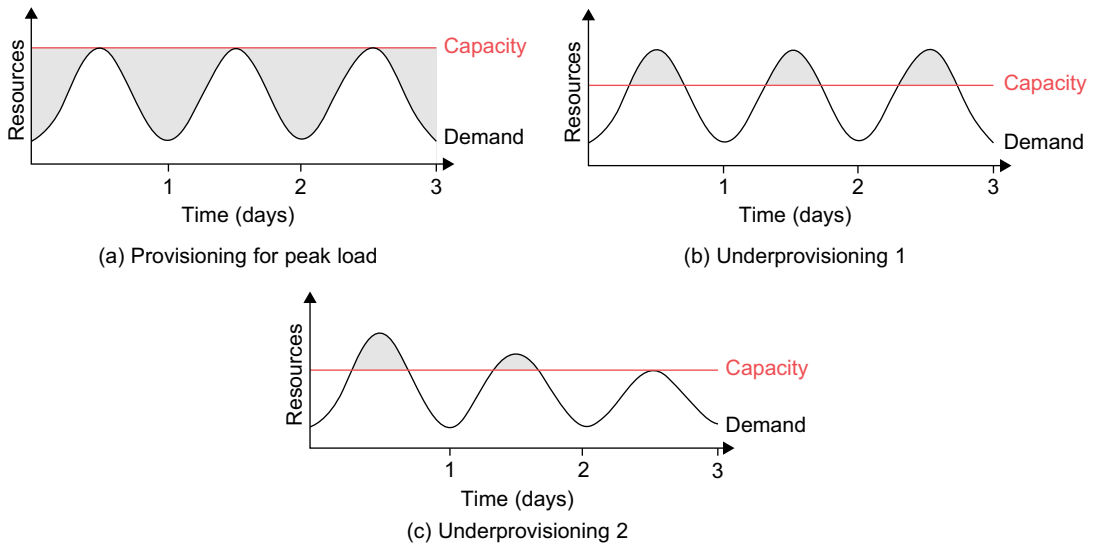


FIGURE 4.24

Three cases of cloud resource provisioning without elasticity: (a) heavy waste due to overprovisioning, (b) underprovisioning and (c) under- and then overprovisioning.

(*Courtesy of Armbrust, et al., UC Berkeley, 2009 [4]*)

on Internet traffic monitored. We characterize these resource provisioning methods as follows (see Figure 4.25).

4.5.2.3 Demand-Driven Resource Provisioning

This method adds or removes computing instances based on the current utilization level of the allocated resources. The demand-driven method automatically allocates two Xeon processors for the user application, when the user was using one Xeon processor more than 60 percent of the time for an extended period. In general, when a resource has surpassed a threshold for a certain amount of time, the scheme increases that resource based on demand. When a resource is below a threshold for a certain amount of time, that resource could be decreased accordingly. Amazon implements such an auto-scale feature in its EC2 platform. This method is easy to implement. The scheme does not work out right if the workload changes abruptly.

The x-axis in Figure 4.25 is the time scale in milliseconds. In the beginning, heavy fluctuations of CPU load are encountered. All three methods have demanded a few VM instances initially. Gradually, the utilization rate becomes more stabilized with a maximum of 20 VMs (100 percent utilization) provided for demand-driven provisioning in Figure 4.25(a). However, the event-driven method reaches a stable peak of 17 VMs toward the end of the event and drops quickly in Figure 4.25(b). The popularity provisioning shown in Figure 4.25(c) leads to a similar fluctuation with peak VM utilization in the middle of the plot.

4.5.2.4 Event-Driven Resource Provisioning

This scheme adds or removes machine instances based on a specific time event. The scheme works better for seasonal or predicted events such as Christmastime in the West and the Lunar New Year in the East. During these events, the number of users grows before the event period and then decreases during the event period. This scheme anticipates peak traffic before it happens. The method results in a minimal loss of QoS, if the event is predicted correctly. Otherwise, wasted resources are even greater due to events that do not follow a fixed pattern.

4.5.2.5 Popularity-Driven Resource Provisioning

In this method, the Internet searches for popularity of certain applications and creates the instances by popularity demand. The scheme anticipates increased traffic with popularity. Again, the scheme has a minimal loss of QoS, if the predicted popularity is correct. Resources may be wasted if traffic does not occur as expected. In Figure 4.25(c), EC2 performance by CPU utilization rate (the dark curve with the percentage scale shown on the left) is plotted against the number of VMs provisioned (the light curves with scale shown on the right, with a maximum of 20 VMs provisioned).

4.5.2.6 Dynamic Resource Deployment

The cloud uses VMs as building blocks to create an execution environment across multiple resource sites. The InterGrid-managed infrastructure was developed by a Melbourne University group [19]. Dynamic resource deployment can be implemented to achieve scalability in performance. The InterGrid is a Java-implemented software system that lets users create execution cloud environments on top of all participating grid resources. Peering arrangements established between gateways enable the allocation of resources from multiple grids to establish the execution environment. In Figure 4.26, a scenario is illustrated by which an *intergrid gateway (IGG)* allocates resources from a local cluster to

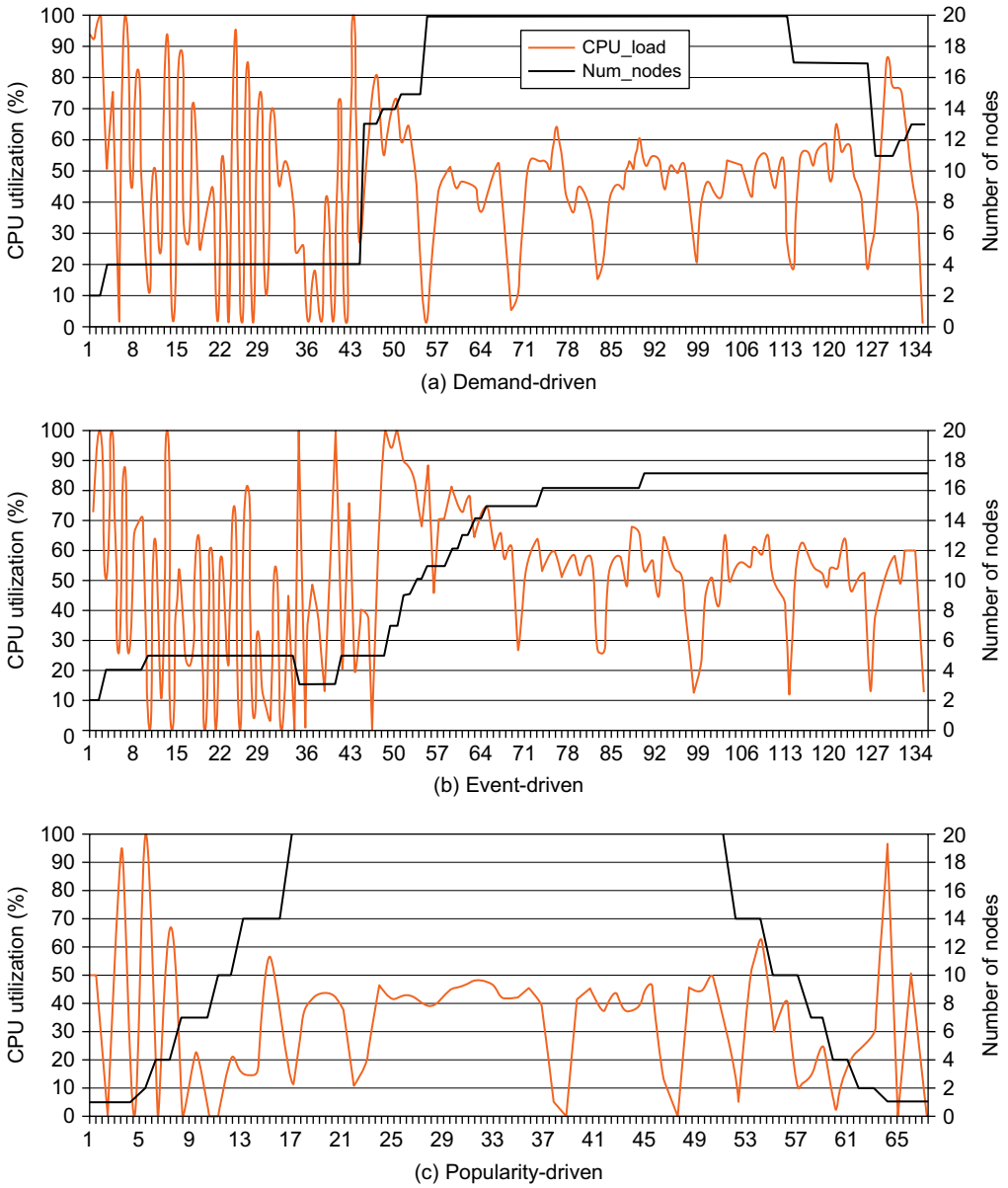


FIGURE 4.25

EC2 performance results on the AWS EC2 platform, collected from experiments at the University of Southern California using three resource provisioning methods.

(*Courtesy of Ken Wu, USC*)

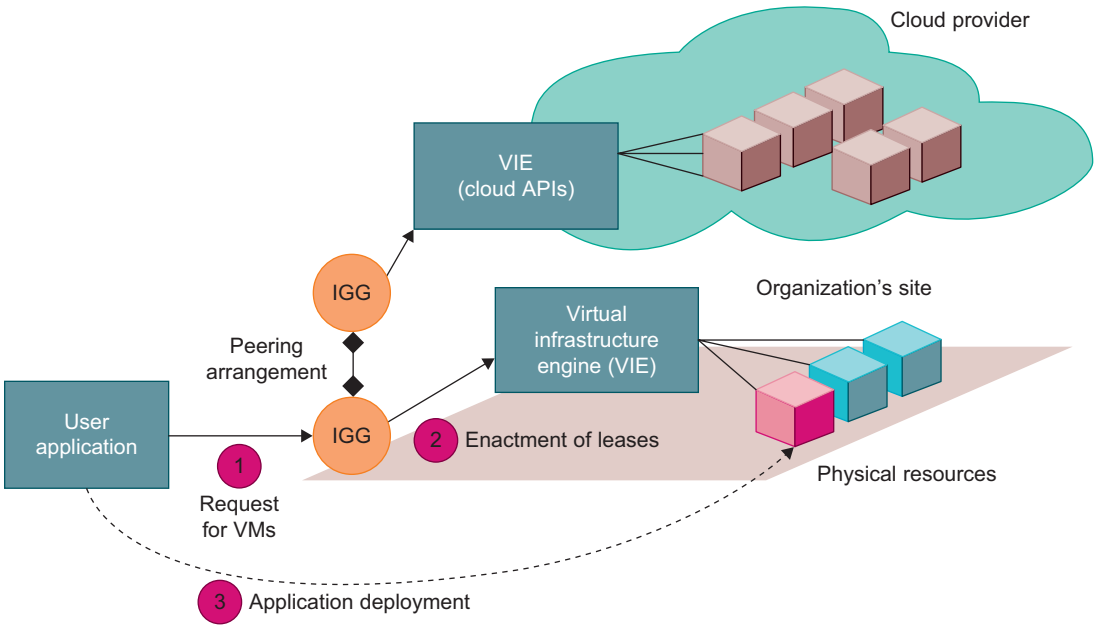


FIGURE 4.26

Cloud resource deployment using an IGG (intergrid gateway) to allocate the VMs from a Local cluster to interact with the IGG of a public cloud provider.

(*Courtesy of Constanzo, et al. © IEEE [21]*)

deploy applications in three steps: (1) requesting the VMs, (2) enacting the leases, and (3) deploying the VMs as requested. Under peak demand, this IGG interacts with another IGG that can allocate resources from a cloud computing provider.

A grid has predefined peering arrangements with other grids, which the IGG manages. Through multiple IGGs, the system coordinates the use of InterGrid resources. An IGG is aware of the peering terms with other grids, selects suitable grids that can provide the required resources, and replies to requests from other IGGs. Request redirection policies determine which peering grid InterGrid selects to process a request and a price for which that grid will perform the task. An IGG can also allocate resources from a cloud provider. The cloud system creates a virtual environment to help users deploy their applications. These applications use the distributed grid resources.

The InterGrid allocates and provides a *distributed virtual environment* (DVE). This is a virtual cluster of VMs that runs isolated from other virtual clusters. A component called the *DVE manager* performs resource allocation and management on behalf of specific user applications. The core component of the IGG is a scheduler for implementing provisioning policies and peering with other gateways. The communication component provides an asynchronous message-passing mechanism. Received messages are handled in parallel by a thread pool.

4.5.2.7 Provisioning of Storage Resources

The data storage layer is built on top of the physical or virtual servers. As the cloud computing applications often provide service to users, it is unavoidable that the data is stored in the clusters of the cloud provider. The service can be accessed anywhere in the world. One example is e-mail systems. A typical large e-mail system might have millions of users and each user can have thousands of e-mails and consume multiple gigabytes of disk space. Another example is a web searching application. In storage technologies, hard disk drives may be augmented with solid-state drives in the future. This will provide reliable and high-performance data storage. The biggest barriers to adopting flash memory in data centers have been price, capacity, and, to some extent, a lack of sophisticated query-processing techniques. However, this is about to change as the I/O bandwidth of solid-state drives becomes too impressive to ignore.

A distributed file system is very important for storing large-scale data. However, other forms of data storage also exist. Some data does not need the namespace of a tree structure file system, and instead, databases are built with stored data files. In cloud computing, another form of data storage is (Key, Value) pairs. Amazon S3 service uses SOAP to access the objects stored in the cloud. Table 4.8 outlines three cloud storage services provided by Google, Hadoop, and Amazon.

Many cloud computing companies have developed large-scale data storage systems to keep huge amount of data collected every day. For example, Google's GFS stores web data and some other data, such as geographic data for Google Earth. A similar system from the open source community is the Hadoop Distributed File System (HDFS) for Apache. Hadoop is the open source implementation of Google's cloud computing infrastructure. Similar systems include Microsoft's Cosmos file system for the cloud.

Despite the fact that the storage service or distributed file system can be accessed directly, similar to traditional databases, cloud computing does provide some forms of structure or semistructure database processing capability. For example, applications might want to process the information contained in a web page. Web pages are an example of semistructural data in HTML format. If some forms of database capability can be used, application developers will construct their application logic more easily. Another reason to build a database-like service in cloud computing is that it will be quite convenient for traditional application developers to code for the cloud platform. Databases are quite common as the underlying storage device for many applications.

Thus, such developers can think in the same way they do for traditional software development. Hence, in cloud computing, it is necessary to build databases like large-scale systems based on data

Table 4.8 Storage Services in Three Cloud Computing Systems

Storage System	Features
GFS: Google File System	Very large sustainable reading and writing bandwidth, mostly continuous accessing instead of random accessing. The programming interface is similar to that of the POSIX file system accessing interface.
HDFS: Hadoop Distributed File System	The open source clone of GFS. Written in Java. The programming interfaces are similar to POSIX but not identical.
Amazon S3 and EBS	S3 is used for retrieving and storing data from/to remote servers. EBS is built on top of S3 for using virtual disks in running EC2 instances.

storage or distributed file systems. The scale of such a database might be quite large for processing huge amounts of data. The main purpose is to store the data in structural or semi-structural ways so that application developers can use it easily and build their applications rapidly. Traditional databases will meet the performance bottleneck while the system is expanded to a larger scale. However, some real applications do not need such strong consistency. The scale of such databases can be quite large. Typical cloud databases include BigTable from Google, SimpleDB from Amazon, and the SQL service from Microsoft Azure.

4.5.3 Virtual Machine Creation and Management

In this section, we will consider several issues for cloud infrastructure management. First, we will consider the resource management of independent service jobs. Then we will consider how to execute third-party cloud applications. Cloud-loading experiments are used by a Melbourne research group on the French Grid'5000 system. This experimental setting illustrates VM creation and management. This case study example reveals major VM management issues and suggests some plausible solutions for workload-balanced execution. Figure 4.27 shows the interactions among VM managers for cloud creation and management. The managers provide a public API for users to submit and control the VMs.

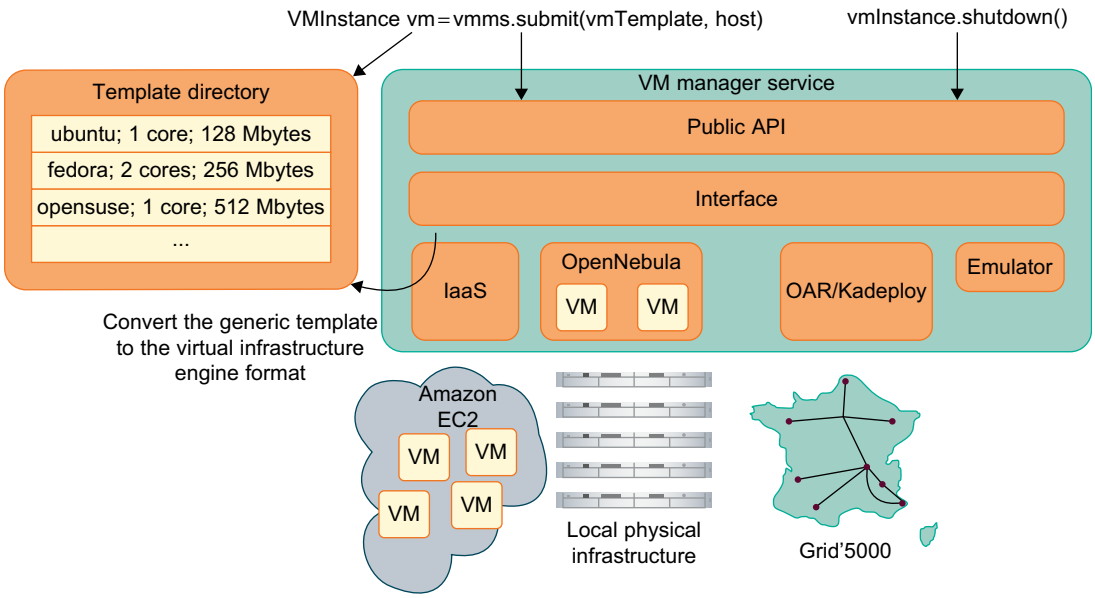


FIGURE 4.27

Interactions among VM managers for cloud creation and management; the manager provides a public API for users to submit and control the VMs.

(*Courtesy of Constanzo, et al. © IEEE [21]*)

4.5.3.1 Independent Service Management

Independent services request facilities to execute many unrelated tasks. Commonly, the APIs provided are some web services that the developer can use conveniently. In Amazon cloud computing infrastructure, SQS is constructed for providing a reliable communication service between different providers. Even the endpoint does not run while another entity has posted a message in SQS. By using independent service providers, the cloud applications can run different services at the same time. Some other services are used for providing data other than the compute or storage services.

4.5.3.2 Running Third-Party Applications

Cloud platforms have to provide support for building applications that are constructed by third-party application providers or programmers. As current web applications are often provided by using Web 2.0 forms (interactive applications with Ajax), the programming interfaces are different from the traditional programming interfaces such as functions in runtime libraries. The APIs are often in the form of services. Web service application engines are often used by programmers for building applications. The web browsers are the user interface for end users.

In addition to gateway applications, the cloud computing platform provides the extra capabilities of accessing backend services or underlying data. As examples, GAE and Microsoft Azure apply their own cloud APIs to get special cloud services. The WebSphere application engine is deployed by IBM for Blue Cloud. It can be used to develop any kind of web application written in Java. In EC2, users can use any kind of application engine that can run in VM instances.

4.5.3.3 Virtual Machine Manager

The VM manager is the link between the gateway and resources. The gateway doesn't share physical resources directly, but relies on virtualization technology for abstracting them. Hence, the actual resources it uses are VMs. The manager manage VMs deployed on a set of physical resources. The VM manager implementation is generic so that it can connect with different VIEs. Typically, VIEs can create and stop VMs on a physical cluster. The Melbourne group has developed managers for OpenNebula, Amazon EC2, and French Grid'5000. The manager using the OpenNebula OS (www.opennebula.org) to deploy VMs on local clusters.

OpenNebula runs as a daemon service on a master node, so the VMM works as a remote user. Users submit VMs on physical machines using different kinds of hypervisors, such as Xen (www.xen.org), which enables the running of several operating systems on the same host concurrently. The VMM also manages VM deployment on grids and IaaS providers. The InterGrid supports Amazon EC2. The connector is a wrapper for the command-line tool Amazon provides. The VM manager for Grid'5000 is also a wrapper for its command-line tools. To deploy a VM, the manager needs to use its template.

4.5.3.4 Virtual Machine Templates

A *VM template* is analogous to a computer's configuration and contains a description for a VM with the following static information:

- The number of cores or processors to be assigned to the VM
- The amount of memory the VM requires
- The kernel used to boot the VM's operating system

- The disk image containing the VM's file system
- The price per hour of using a VM

The gateway administrator provides the VM template information when the infrastructure is set up. The administrator can update, add, and delete templates at any time. In addition, each gateway in the InterGrid network must agree on the templates to provide the same configuration on each site. To deploy an instance of a given VM, the VMM generates a descriptor from the template. This descriptor contains the same fields as the template and additional information related to a specific VM instance. Typically the additional information includes:

- The disk image that contains the VM's file system
- The address of the physical machine hosting the VM
- The VM's network configuration
- The required information for deployment on an IaaS provider

Before starting an instance, the scheduler gives the network configuration and the host's address; it then allocates MAC and IP addresses for that instance. The template specifies the disk image field. To deploy several instances of the same VM template in parallel, each instance uses a temporary copy of the disk image. Hence, the descriptor contains the path to the copied disk image. The descriptor's fields are different for deploying a VM on an IaaS provider. Network information is not needed, because Amazon EC2 automatically assigns a public IP to the instances. The IGG works with a repository of VM templates, called the *VM template directory*.

4.5.3.5 Distributed VM Management

Figure 4.30 illustrates the interactions between InterGrid's components. A distributed VM manager makes requests for VMs and queries their status. This manager requests VMs from the gateway on behalf of the user application. The manager obtains the list of requested VMs from the gateway. This list contains a tuple of public IP/private IP addresses for each VM with Secure Shell (SSH) tunnels. Users must specify which VM template they want to use and the number of VM instances needed, the deadline, the wall time, and the address for an alternative gateway.

The local gateway tries to obtain resources from the underlying VIEs. When this is impossible, the local gateway starts a negotiation with any remote gateways to fulfill the request. When a gateway schedules the VMs, it sends the VM access information to the requester gateway. Finally, the manager configures the VM, sets up SSH tunnels, and executes the tasks on the VM. Under the peering policy, each gateway's scheduler uses conservative backfilling to schedule requests. When the scheduler can't start a request immediately using local resources, a redirection algorithm will be initiated.

Example 4.6 Experiments on an InterGrid Test Bed over the Grid'5000

The Melbourne group conducted two experiments to evaluate the InterGrid architecture. The first one evaluates the performance of allocation decisions by measuring how the IGG manages load via peering arrangements. The second considers its effectiveness in deploying a bag-of-tasks application. The experiment was conducted on the French experimental grid platform Grid'5000. Grid'5000 comprises 4,792 processor cores on nine grid sites across France. Each gateway represents one Grid'5000 site, as shown in Figure 4.28.

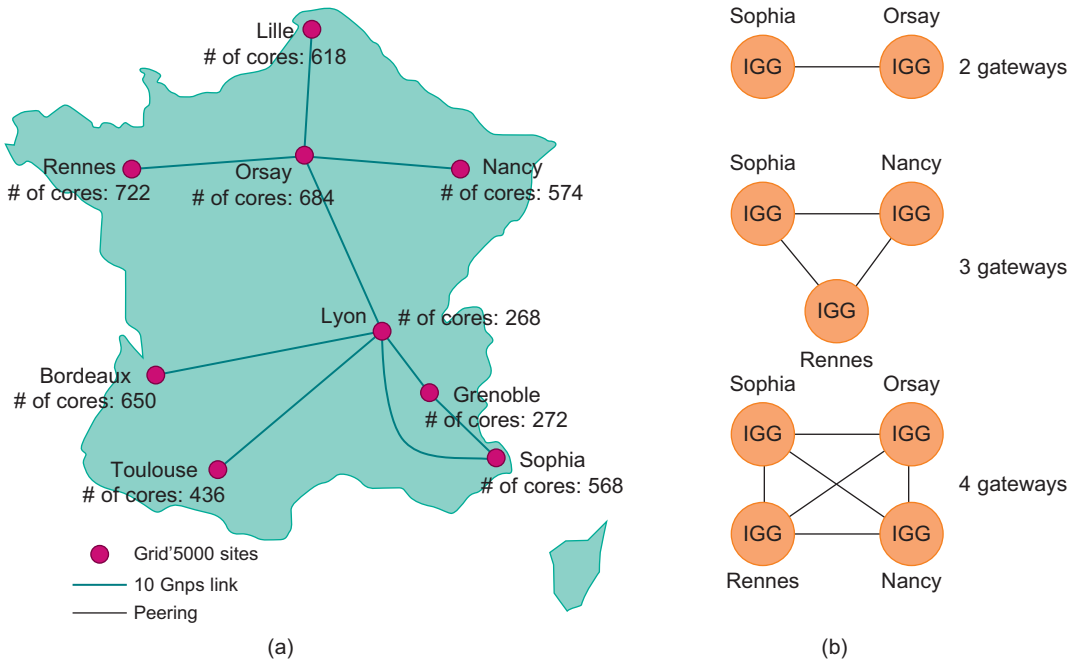


FIGURE 4.28

The InterGrid test bed over the French Grid'5000 located in nine cities across France.

(*Courtesy of Constanzo, et al. © IEEE [21]*)

To prevent the gateways from interfering with real Grid'5000 users, emulated VM managers were implemented to instantiate fictitious VMs. The number of emulated hosts is limited by the core number at each site. A balanced workload was configured among the sites. The maximum number of VMs requested does not exceed the number of cores in any site. The load characteristics are shown in Figure 4.29 under a four-gateway scenario. The teal bars indicate each grid site's load. The magenta bars show the load when gateways redirect requests to one another. The green bars correspond to the amount of load each gateway accepts from other gateways. The brown bars represent the amount of load that is redirected. The results show that the loading policy can balance the load across the nine sites. Rennes, a site with a heavy load, benefits from peering with other gateways as the gateway redirects a great share of its load to other sites.

4.5.4 Global Exchange of Cloud Resources

In order to support a large number of application service consumers from around the world, cloud infrastructure providers (i.e., IaaS providers) have established data centers in multiple geographical locations to provide redundancy and ensure reliability in case of site failures. For example, Amazon

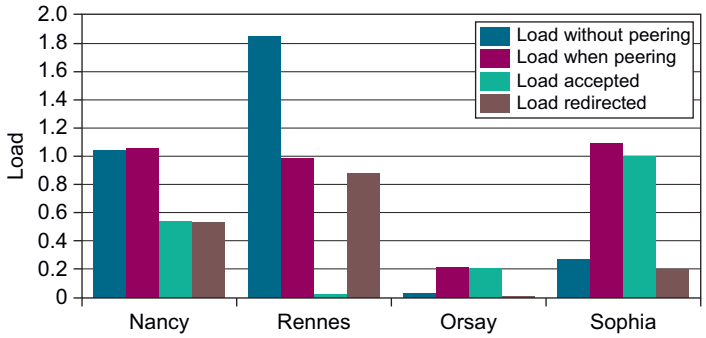


FIGURE 4.29

Cloud loading results at four gateways at resource sites in the Grid'5000 system.

(*Courtesy of Constanzo, et al. © IEEE [21]*)

has data centers in the United States (e.g., one on the East Coast and another on the West Coast) and Europe. However, currently Amazon expects its cloud customers (i.e., SaaS providers) to express a preference regarding where they want their application services to be hosted. Amazon does not provide seamless/automatic mechanisms for scaling its hosted services across multiple geographically distributed data centers.

This approach has many shortcomings. First, it is difficult for cloud customers to determine in advance the best location for hosting their services as they may not know the origin of consumers of their services. Second, SaaS providers may not be able to meet the QoS expectations of their service consumers originating from multiple geographical locations. This necessitates building mechanisms for seamless federation of data centers of a cloud provider or providers supporting dynamic scaling of applications across multiple domains in order to meet QoS targets of cloud customers. Figure 4.30 shows the high-level components of the Melbourne group's proposed InterCloud architecture.

In addition, no single cloud infrastructure provider will be able to establish its data centers at all possible locations throughout the world. As a result, cloud application service (SaaS) providers will have difficulty in meeting QoS expectations for all their consumers. Hence, they would like to make use of services of multiple cloud infrastructure service providers who can provide better support for their specific consumer needs. This kind of requirement often arises in enterprises with global operations and applications such as Internet services, media hosting, and Web 2.0 applications. This necessitates federation of cloud infrastructure service providers for seamless provisioning of services across different cloud providers. To realize this, the Cloudbus Project at the University of Melbourne has proposed InterCloud architecture [12] supporting brokering and exchange of cloud resources for scaling applications across multiple clouds.

By realizing InterCloud architectural principles in mechanisms in their offering, cloud providers will be able to dynamically expand or resize their provisioning capability based on sudden spikes in workload demands by leasing available computational and storage capabilities from other cloud

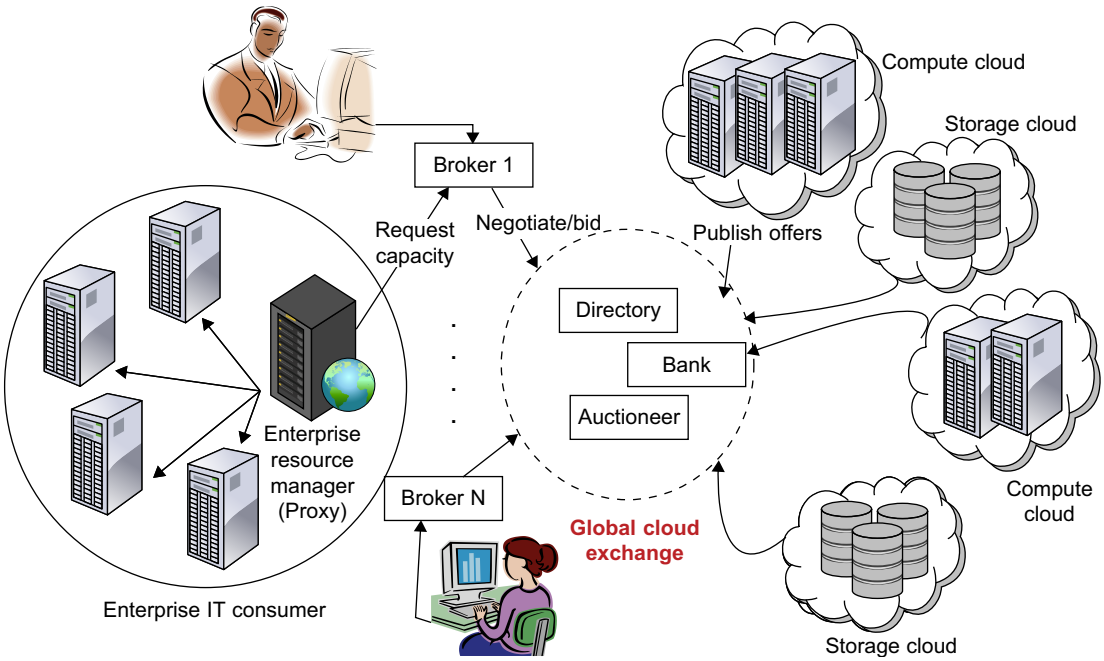


FIGURE 4.30

Inter-cloud exchange of cloud resources through brokering.

(*Courtesy of R. Buyya, et al., University of Melbourne [12]*)

service providers; operate as part of a market-driven resource leasing federation, where application service providers such as Salesforce.com host their services based on negotiated SLA contracts driven by competitive market prices; and deliver on-demand, reliable, cost-effective, and QoS-aware services based on virtualization technologies while ensuring high QoS standards and minimizing service costs. They need to be able to utilize market-based utility models as the basis for provisioning of virtualized software services and federated hardware infrastructure among users with heterogeneous applications.

They consist of client brokering and coordinator services that support utility-driven federation of clouds: application scheduling, resource allocation, and migration of workloads. The architecture cohesively couples the administratively and topologically distributed storage and compute capabilities of clouds as part of a single resource leasing abstraction. The system will ease the cross-domain capability integration for on-demand, flexible, energy-efficient, and reliable access to the infrastructure based on virtualization technology [6,75].

The *Cloud Exchange (CEx)* acts as a market maker for bringing together service producers and consumers. It aggregates the infrastructure demands from application brokers and evaluates them against the available supply currently published by the cloud coordinators. It supports trading of cloud services based on competitive economic models such as commodity markets and auctions. CEx allows participants to locate providers and consumers with fitting offers. Such markets enable

services to be commoditized, and thus will pave the way for creation of dynamic market infrastructure for trading based on SLAs. An SLA specifies the details of the service to be provided in terms of metrics agreed upon by all parties, and incentives and penalties for meeting and violating the expectations, respectively. The availability of a banking system within the market ensures that financial transactions pertaining to SLAs between participants are carried out in a secure and dependable environment.

4.6 CLOUD SECURITY AND TRUST MANAGEMENT

Lacking trust between service providers and cloud users has hindered the universal acceptance of cloud computing as a service on demand. In the past, trust models have been developed to protect mainly e-commerce and online shopping provided by eBay and Amazon. For web and cloud services, trust and security become even more demanding, because leaving user applications completely to the cloud providers has faced strong resistance by most PC and server users. Cloud platforms become worrisome to some users for lack of privacy protection, security assurance, and copyright protection. Trust is a social problem, not a pure technical issue. However, the social problem can be solved with a technical approach.

Common sense dictates that technology can enhance trust, justice, reputation, credit, and assurance in Internet applications. As a virtual environment, the cloud poses new security threats that are more difficult to contain than traditional client and server configurations. To solve these trust problems, a new data-protection model is presented in this section. In many cases, one can extend the trust models for P2P networks and grid systems to protect clouds and data centers.

4.6.1 Cloud Security Defense Strategies

A healthy cloud ecosystem is desired to free users from abuses, violence, cheating, hacking, viruses, rumors, pornography, spam, and privacy and copyright violations. The security demands of three cloud service models, IaaS, PaaS, and SaaS, are described in this section. These security models are based on various SLAs between providers and users.

4.6.1.1 Basic Cloud Security

Three basic cloud security enforcements are expected. First, facility security in data centers demands on-site security year round. Biometric readers, CCTV (close-circuit TV), motion detection, and man traps are often deployed. Also, network security demands fault-tolerant external firewalls, intrusion detection systems (IDSes), and third-party vulnerability assessment. Finally, platform security demands SSL and data decryption, strict password policies, and system trust certification. Figure 4.31 shows the mapping of cloud models, where special security measures are deployed at various cloud operating levels.

Servers in the cloud can be physical machines or VMs. User interfaces are applied to request services. The provisioning tool carves out the systems from the cloud to satisfy the requested service. A security-aware cloud architecture demands security enforcement. Malware-based attacks such as network worms, viruses, and DDoS attacks exploit system vulnerabilities. These attacks compromise system functionality or provide intruders unauthorized access to critical information.

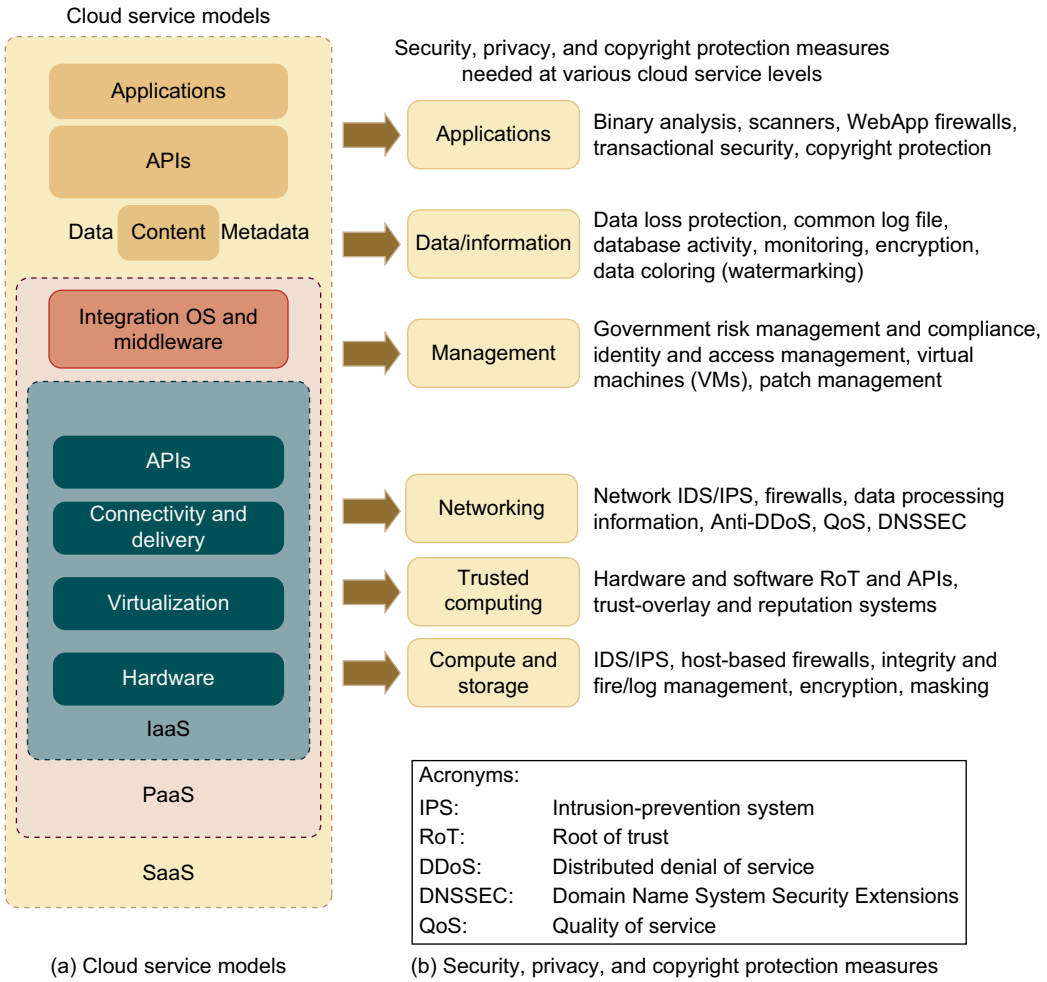


FIGURE 4.31

Cloud service models on the left (a) and corresponding security measures on the right (b); the IaaS is at the innermost level, PaaS is at the middle level, and SaaS is at the outermost level, including all hardware, software, datasets, and networking resources.

(*Courtesy of Hwang and Li [36]*)

Thus, security defenses are needed to protect all cluster servers and data centers. Here are some cloud components that demand special security protection:

- Protection of servers from malicious software attacks such as worms, viruses, and malware
- Protection of hypervisors or VM monitors from software-based attacks and vulnerabilities
- Protection of VMs and monitors from service disruption and DoS attacks

- Protection of data and information from theft, corruption, and natural disasters
- Providing authenticated and authorized access to critical data and services

4.6.1.2 Security Challenges in VMs

As we discussed earlier in this chapter, traditional network attacks include buffer overflows, DoS attacks, spyware, malware, rootkits, Trojan horses, and worms. In a cloud environment, newer attacks may result from hypervisor malware, guest hopping and hijacking, or VM rootkits. Another type of attack is the man-in-the-middle attack for VM migrations. In general, passive attacks steal sensitive data or passwords. Active attacks may manipulate kernel data structures which will cause major damage to cloud servers. An IDS can be a NIDS or a HIDS. Program shepherding can be applied to control and verify code execution. Other defense technologies include using the RIO dynamic optimization infrastructure, or VMware's vSafe and vShield tools, security compliance for hypervisors, and Intel vPro technology. Others apply a hardened OS environment or use isolated execution and sandboxing.

4.6.1.3 Cloud Defense Methods

Virtualization enhances cloud security. But VMs add an additional layer of software that could become a single point of failure. With virtualization, a single physical machine can be divided or partitioned into multiple VMs (e.g., server consolidation). This provides each VM with better security isolation and each partition is protected from DoS attacks by other partitions. Security attacks in one VM are isolated and contained from affecting the other VMs. Table 4.9 lists eight protection schemes to secure public clouds and data centers. VM failures do not propagate to other VMs. The

Table 4.9 Physical and Cyber Security Protection at Cloud/Data Centers

Protection Schemes	Brief Description and Deployment Suggestions
Secure data centers and computer buildings	Choose hazard-free location, enforce building safety. Avoid windows, keep buffer zone around the site, bomb detection, camera surveillance, earthquake-proof, etc.
Use redundant utilities at multiple sites	Multiple power and supplies, alternate network connections, multiple databases at separate sites, data consistency, data watermarking, user authentication, etc.
Trust delegation and negotiation	Cross certificates to delegate trust across PKI domains for various data centers, trust negotiation among certificate authorities (CAs) to resolve policy conflicts
Worm containment and DDoS defense	Internet worm containment and distributed defense against DDoS attacks to secure all data centers and cloud platforms
Reputation system for data centers	Reputation system could be built with P2P technology; one can build a hierarchy of reputation systems from data centers to distributed file systems
Fine-grained file access control	Fine-grained access control at the file or object level; this adds to security protection beyond firewalls and IDSes
Copyright protection and piracy prevention	Piracy prevention achieved with peer collusion prevention, filtering of poisoned content, nondestructive read, alteration detection, etc.
Privacy protection	Uses double authentication, biometric identification, intrusion detection and disaster recovery, privacy enforcement by data watermarking, data classification, etc.

hypervisor provides visibility of the guest OS, with complete guest isolation. Fault containment and failure isolation of VMs provide a more secure and robust environment. Malicious intrusions may destroy valuable hosts, networks, and storage resources. Internet anomalies found in routers, gateways, and distributed hosts may stop cloud services. Trust negotiation is often done at the SLA level. Public Key Infrastructure (PKI) services could be augmented with data-center reputation systems. Worm and DDoS attacks must be contained. It is harder to establish security in the cloud because all data and software are shared by default.

4.6.1.4 Defense with Virtualization

The VM is decoupled from the physical hardware. The entire VM can be represented as a software component and can be regarded as binary or digital data. The VM can be saved, cloned, encrypted, moved, or restored with ease. VMs enable HA and faster disaster recovery. Live migration of VMs was suggested by many researchers [36] for building *distributed intrusion detection systems (DIDSes)*. Multiple IDS VMs can be deployed at various resource sites including data centers. DIDS design demands trust negation among PKI domains. Security policy conflicts must be resolved at design time and updated periodically.

4.6.1.5 Privacy and Copyright Protection

The user gets a predictable configuration before actual system integration. Yahoo!'s Pipes is a good example of a lightweight cloud platform. With shared files and data sets, privacy, security, and copyright data could be compromised in a cloud computing environment. Users desire to work in a software environment that provides many useful tools to build cloud applications over large data sets. Google's platform essentially applies in-house software to protect resources. The Amazon EC2 applies HMEC and X.509 certificates in securing resources. It is necessary to protect browser-initiated application software in the cloud environment. Here are several security features desired in a secure cloud:

- Dynamic web services with full support from secure web technologies
- Established trust between users and providers through SLAs and reputation systems
- Effective user identity management and data-access management
- Single sign-on and single sign-off to reduce security enforcement overhead
- Auditing and copyright compliance through proactive enforcement
- Shifting of control of data operations from the client environment to cloud providers
- Protection of sensitive and regulated information in a shared environment

Example 4.7 Cloud Security Safeguarded by Gateway and Firewalls

Figure 4.32 shows a security defense system for a typical private cloud environment. The gateway is fully secured to protect access to commercial clouds that are wide open to the general public. The firewall provides an external shield. The gateway secures the application server, message queue, database, web service client, and browser with HTTP, JMS, SQL, XML, and SSL security protocols, etc. The defense scheme is needed to protect user data from server attacks. A user's private data must not be leaked to other users without permission.

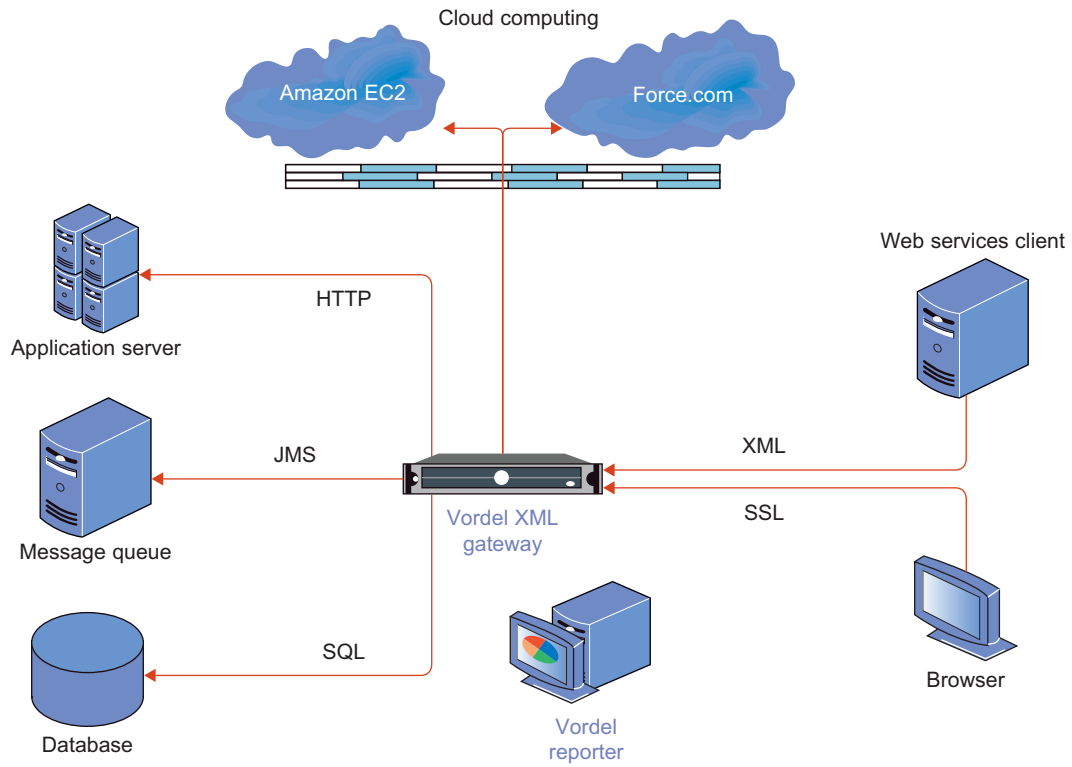


FIGURE 4.32

The typical security structure coordinated by a secured gateway plus external firewalls to safeguard the access of public or private clouds.

(*Courtesy of Vordel Company*)

4.6.2 Distributed Intrusion/Anomaly Detection

Data security is the weakest link in all cloud models. We need new cloud security standards to apply common API tools to cope with the data lock-in problem and network attacks or abuses. The IaaS model represented by Amazon is most sensitive to external attacks. Role-based interface tools alleviate the complexity of the provisioning system. For example, IBM's Blue Cloud provisions through a role-based web portal. A SaaS bureau may order secretarial services from a common cloud platform. Many IT companies are now offering cloud services with no guaranteed security.

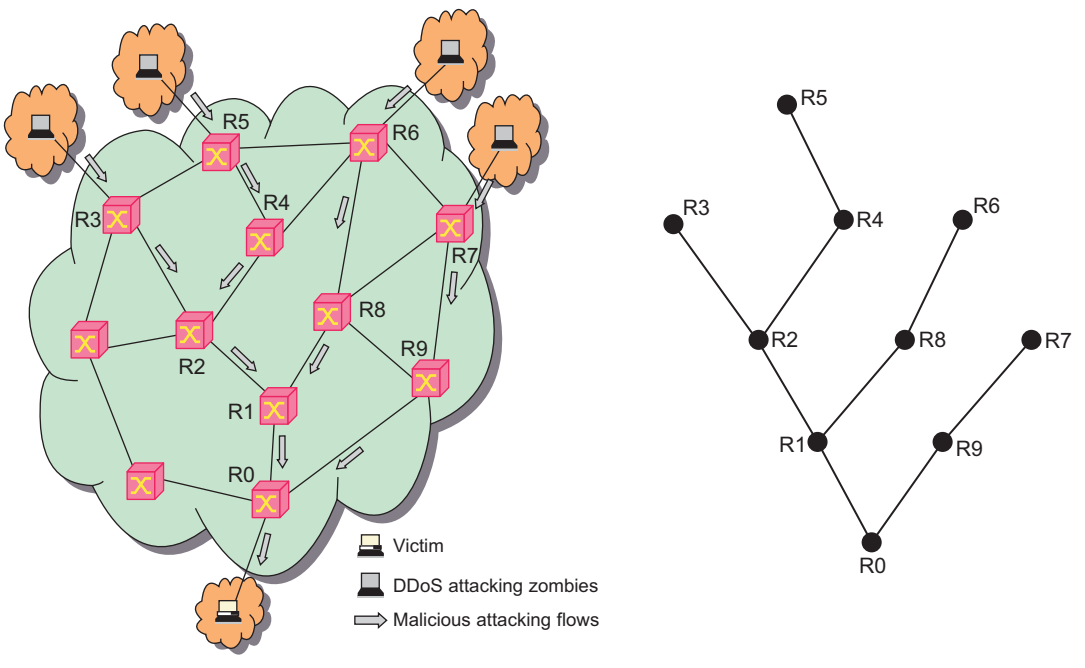
Security threats may be aimed at VMs, guest OSes, and software running on top of the cloud. IDSes attempt to stop these attacks before they take effect. Both signature matching and anomaly detection can be implemented on VMs dedicated to building IDSes. Signature-matching IDS

technology is more mature, but require frequent updates of the signature databases. Network anomaly detection reveals abnormal traffic patterns, such as unauthorized episodes of TCP connection sequences, against normal traffic patterns. Distributed IDSes are needed to combat both types of intrusions.

4.6.2.1 Distributed Defense against DDoS Flooding Attacks

A DDoS defense system must be designed to cover multiple network domains spanned by a given cloud platform. These network domains cover the edge networks where cloud resources are connected. DDoS attacks come with widespread worms. The flooding traffic is large enough to crash the victim server by buffer overflow, disk exhaustion, or connection saturation. Figure 4.33(a) shows a flooding attack pattern. Here, the hidden attacker launched the attack from many zombies toward a victim server at the bottom router R_0.

The flooding traffic flows essentially with a tree pattern shown in Figure 4.33(b). Successive attack-transit routers along the tree reveal the abnormal surge in traffic. This DDoS defense system is based on change-point detection by all routers. Based on the anomaly pattern detected in covered network domains, the scheme detects a DDoS attack before the victim is overwhelmed. The



(a) Traffic flow pattern of a DDoS attack

(b) The attack traffic flow tree over 10 routers

FIGURE 4.33

DDoS attacks and defense by change-point detection at all routers on the flooding tree.

(*Courtesy of Chen, Hwang, and Ku [15]*)

detection scheme is suitable for protecting cloud core networks. The provider-level cooperation eliminates the need for intervention by edge networks.

Example 4.8 Man-in-the-Middle Attacks

Figure 4.34 shows VM migration from host machine VMM A to host machine VMM B, via a security vulnerable network. In a man-in-the-middle attack, the attacker can view the VM contents being migrated, steal sensitive data, or even modify the VM-specific contents including the OS and application states. An attacker posing this attack can launch an active attack to insert a VM-based rootkit into the migrating VM, which can subvert the entire operation of the migration process without the knowledge of the guest OS and embedded application.

4.6.3 Data and Software Protection Techniques

In this section, we will introduce a data coloring technique to preserve data integrity and user privacy. Then we will discuss a watermarking scheme to protect software files from being widely distributed in a cloud environment.

4.6.3.1 Data Integrity and Privacy Protection

Users desire a software environment that provides many useful tools to build cloud applications over large data sets. In addition to application software for MapReduce, BigTable, EC2, 3S, Hadoop, AWS, GAE, and WebSphere2, users need some security and privacy protection software for using the cloud. Such software should offer the following features:

- Special APIs for authenticating users and sending e-mail using commercial accounts
- Fine-grained access control to protect data integrity and deter intruders or hackers
- Shared data sets protected from malicious alteration, deletion, or copyright violation

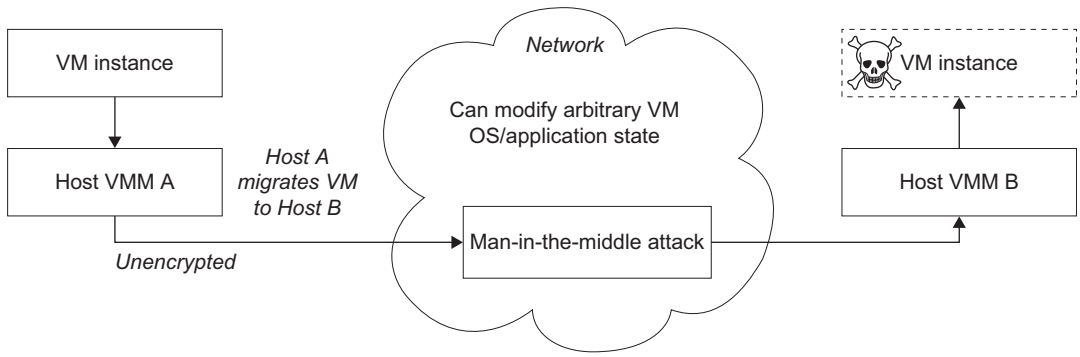


FIGURE 4.34

A VM migrating from host A to host B through a vulnerable network threatened by a man-in-the-middle attack to modify the VM template and OS state.

- Ability to secure the ISP or cloud service provider from invading users' privacy
- Personal firewalls at user ends to keep shared data sets from Java, JavaScript, and ActiveX applets
- A privacy policy consistent with the cloud service provider's policy, to protect against identity theft, spyware, and web bugs
- VPN channels between resource sites to secure transmission of critical data objects

4.6.3.2 Data Coloring and Cloud Watermarking

With shared files and data sets, privacy, security, and copyright information could be compromised in a cloud computing environment. Users desire to work in a trusted software environment that provides useful tools to build cloud applications over protected data sets. In the past, watermarking was mainly used for digital copyright management. As shown in Figure 4.35, the system generates special colors for each data object. Data coloring means labeling each data object by a unique color. Differently colored data objects are thus distinguishable.

The user identification is also colored to be matched with the data colors. This color matching process can be applied to implement different trust management events. Cloud storage provides a process for the generation, embedding, and extraction of the watermarks in colored objects. Interested readers may refer to the articles by Hwang and Li [36] for details on the data coloring and matching process. In general, data protection was done by encryption or decryption which is

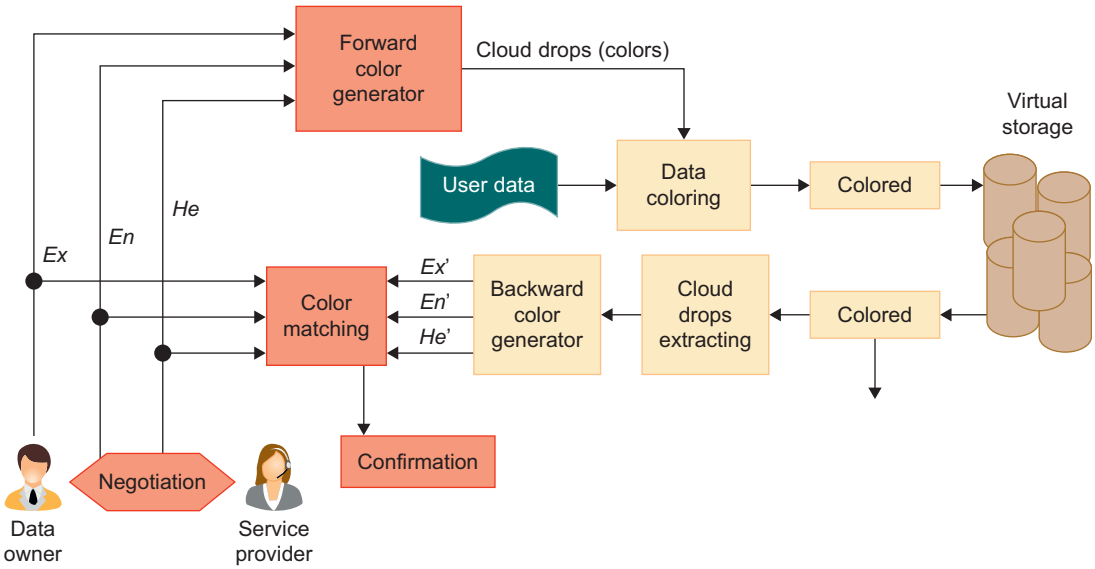


FIGURE 4.35

Data coloring with cloud watermarking for trust management at various security clearance levels in data centers.

(*Courtesy of Hwang and Li [36]*)

computationally expensive. The data coloring takes a minimal number of calculations to color or decolor the data objects. Cryptography and watermarking or coloring can be used jointly in a cloud environment.

4.6.3.3 Data Lock-in Problem and Proactive Solutions

Cloud computing moves both the computation and the data to the server clusters maintained by cloud service providers. Once the data is moved into the cloud, users cannot easily extract their data and programs from cloud servers to run on another platform. This leads to a data lock-in problem. This has hindered the use of cloud computing. Data lock-in is attributed to two causes: lack of interoperability, whereby each cloud vendor has its proprietary API that limits users to extract data once submitted; and lack of application compatibility, in that most computing clouds expect users to write new applications from scratch, when they switch cloud platforms.

One possible solution to data lock-in is the use of standardized cloud APIs. This requires building standardized virtual platforms that adhere to OVF, a platform-independent, efficient, extensible, and open format for VMs. This will enable efficient, secure software distribution, facilitating the mobility of VMs. Using OVF one can move data from one application to another. This will enhance QoS, and thus enable cross-cloud applications, allowing workload migration among data centers to user-specific storage. By deploying applications, users can access and intermix applications across different cloud services.

4.6.4 Reputation-Guided Protection of Data Centers

Trust is a personal opinion, which is very subjective and often biased. Trust can be transitive but not necessarily symmetric between two parties. Reputation is a public opinion, which is more objective and often relies on a large opinion aggregation process to evaluate. Reputation may change or decay over time. Recent reputation should be given more preference than past reputation. In this section, we review the reputation systems for protecting data centers or cloud user communities.

4.6.4.1 Reputation System Design Options

Figure 4.36 provides an overview of reputation system design options. Public opinion on the character or standing (such as honest behavior or reliability) of an entity could be the reputation of a person, an agent, a product, or a service. It represents a collective evaluation by a group of people/agents and resource owners. Many reputation systems have been proposed in the past mainly for P2P, multiagent, or e-commerce systems.

To address reputation systems for cloud services, a systematic approach is based on the design criteria and administration of the reputation systems. Figure 4.36 shows a two-tier classification of existing reputation systems that have been proposed in recent years. Most of them were designed for P2P or social networks. These reputation systems can be converted for protecting cloud computing applications. In general, the reputation systems are classified as *centralized* or *distributed* depending on how they are implemented. In a centralized system, a single central authority is responsible for managing the reputation system, while the distributed model involves multiple control centers working collectively. Reputation-based trust management and techniques for securing P2P and social networks could be merged to defend data centers and cloud platforms against attacks from the open network.

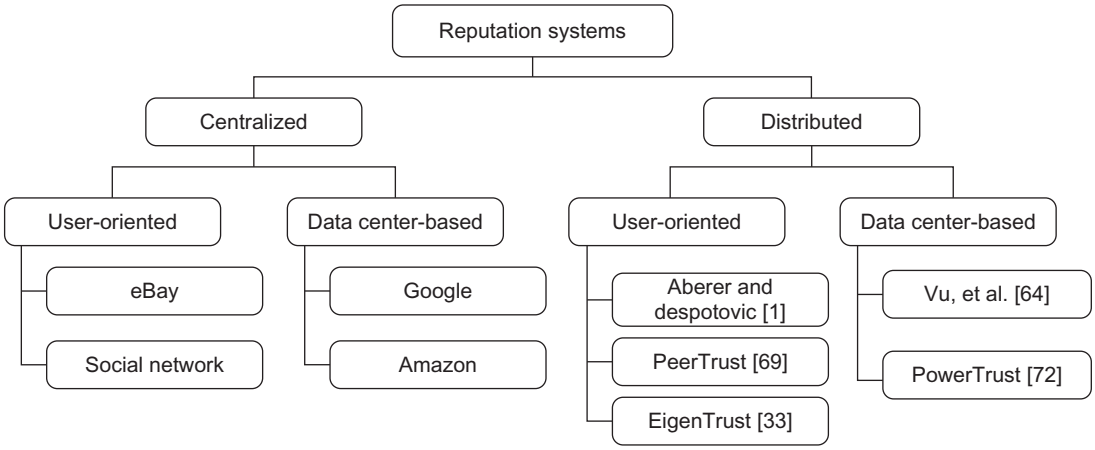


FIGURE 4.36

Design options of reputation systems for social networks and cloud platforms.

A centralized reputation system is easier to implement, but demands more powerful and reliable server resources; a distributed reputation system is much more complex to build. Distributed systems are more scalable and reliable in terms of handling failures. At the second tier, reputation systems are further classified by the scope of reputation evaluation. *User-oriented* reputation systems focus on individual users or agents. Most P2P reputation systems belong to this category. In data centers, reputation is modeled for the resource site as a whole. This reputation applies to products or services offered by the cloud. Commercial reputation systems have been built by eBay, Google, and Amazon in connection with the services they provide. These are centralized reputation systems.

Distributed reputation systems are mostly developed by academic research communities. Aberer and Despotovic have proposed a model to manage trust in P2P systems. The Eigentrust reputation system was developed at Stanford University using a trust matrix approach. The PeerTrust system was developed at Georgia Institute of Technology for supporting e-commerce applications. The PowerTrust system was developed at the University of Southern California based on Power law characteristics of Internet traffic for P2P applications. Vu, et al. proposed a QoS-based ranking system for P2P transactions.

4.6.4.2 Reputation Systems for Clouds

Redesigning the aforementioned reputation systems for protecting data centers offers new opportunities for expanded applications beyond P2P networks. Data consistency is checked across multiple databases. Copyright protection secures wide-area content distributions. To separate user data from specific SaaS programs, providers take the most responsibility in maintaining data integrity and consistency. Users can switch among different services using their own data. Only the users have the keys to access the requested data.

The data objects must be uniquely named to ensure global consistency. To ensure data consistency, unauthorized updates of data objects by other cloud users are prohibited. The reputation system

can be implemented with a trust overlay network. A hierarchy of P2P reputation systems is suggested to protect cloud resources at the site level and data objects at the file level. This demands both coarse-grained and fine-grained access control of shared resources. These reputation systems keep track of security breaches at all levels.

The reputation system must be designed to benefit both cloud users and data centers. Data objects used in cloud computing reside in multiple data centers over a SAN. In the past, most reputation systems were designed for P2P social networking or for online shopping services. These reputation systems can be converted to protect cloud platform resources or user applications in the cloud. A centralized reputation system is easier to implement, but demands more powerful and reliable server resources. Distributed reputation systems are more scalable and reliable in terms of handling failures. The five security mechanisms presented earlier can be greatly assisted by using a reputation system specifically designed for data centers.

However, it is possible to add social tools such as reputation systems to support safe cloning of VMs. Snapshot control is based on the defined RPO. Users demand new security mechanisms to protect the cloud. For example, one can apply secured information logging, migrate over secured virtual LANs, and apply ECC-based encryption for secure migration. Sandboxes provide a safe execution platform for running programs. Further, sandboxes can provide a tightly controlled set of resources for guest operating systems, which allows a security test bed to test the application code from third-party vendors.

4.6.4.3 Trust Overlay Networks

Reputation represents a collective evaluation by users and resource owners. Many reputation systems have been proposed in the past for P2P, multiagent, or e-commerce systems. To support trusted cloud services, Hwang and Li [36] have suggested building a *trust overlay network* to model trust relationships among data-center modules. This trust overlay could be structured with a *distributed hash table (DHT)* to achieve fast aggregation of global reputations from a large number of local reputation scores. This trust overlay design was first introduced in [12]. Here, the designer needs to have two layers for fast reputation aggregation, updating, and dissemination to all users. Figure 4.37 shows construction of the two layers of the trust overlay network.

At the bottom layer is the trust overlay for distributed trust negotiation and reputation aggregation over multiple resource sites. This layer handles user/server authentication, access authorization, trust delegation, and data integrity control. At the top layer is an overlay for fast virus/worm signature generation and dissemination and for piracy detection. This overlay facilitates worm containment and IDSes against viruses, worms, and DDoS attacks. The content poisoning technique [6] is reputation-based. This protection scheme can stop copyright violations in a cloud environment over multiple data centers.

The reputation system enables trusted interactions between cloud users and data-center owners. Privacy is enforced by matching colored user identifications with the colored data objects. The use of content poisoning was suggested to protect copyright of digital content [46]. The security-aware cloud architecture (see Figure 4.14) is specially tailored to protect virtualized cloud infrastructure. The trust of provided cloud platforms comes from not only SLAs, but also from effective enforcement of security policies and deployment of countermeasures to defend against network attacks. By varying security control standards, one can cope with the dynamic variation of cloud operating

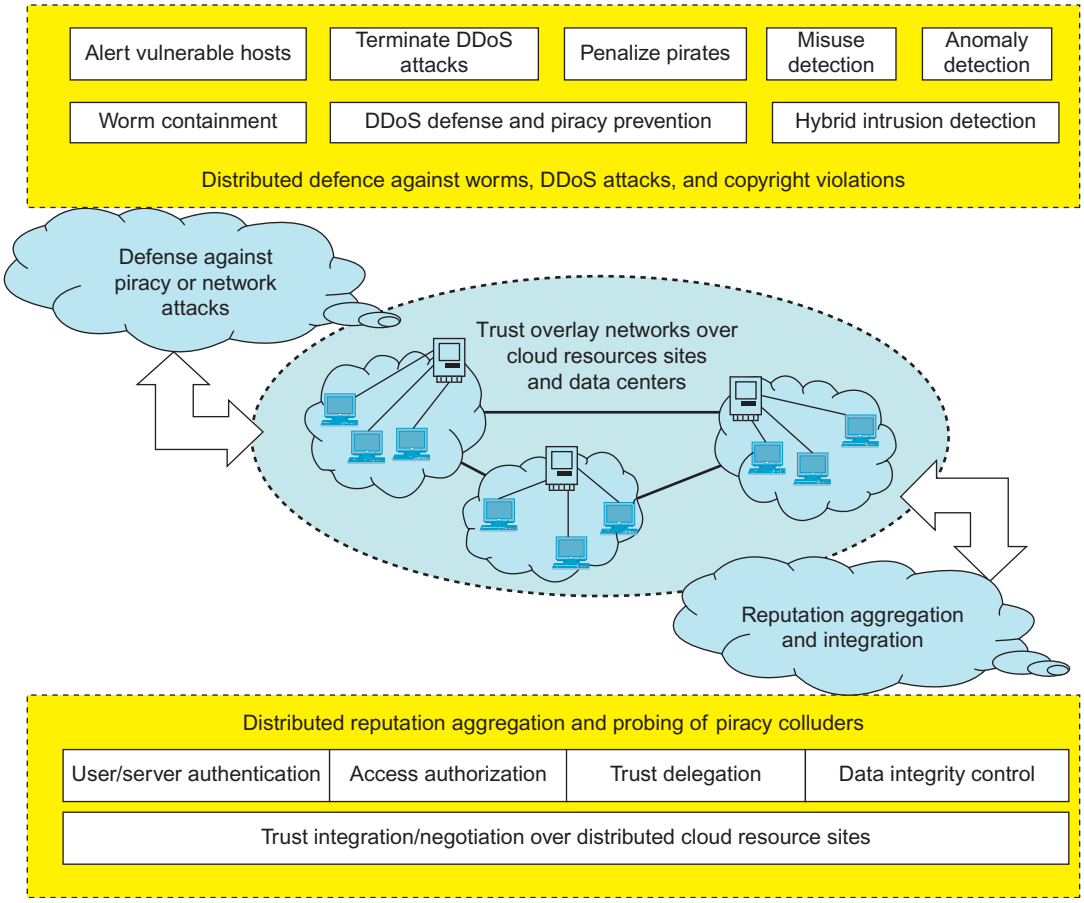


FIGURE 4.37

DHT-based trust overlay networks built over cloud resources provisioned from multiple data centers for trust management and distributed security enforcement.

(*Courtesy of Hwang and Li [36]*)

conditions. The design is aimed at a trusted cloud environment to ensure high-quality services, including security.

The cloud security trend is to apply virtualization support for security enforcement in data centers. Both reputation systems and data watermarking mechanisms can protect data-center access at the coarse-grained level and to limit data access at the fine-grained file level. In the long run, a new *Security as a Service* is desired. This "SaaS" is crucial to the universal acceptance of web-scale cloud computing in personal, business, community, and government applications. Internet clouds are certainly in line with IT globalization and efficient computer outsourcing. However, interoperability among different clouds relies on a common operational standard by building a healthy cloud ecosystem.