Module-4: Cloud Computing Architecture

1. Introduction

Utility-oriented data centers are the first outcome of cloud computing for and they serve as the infrastructure through which the services are implemented and delivered.

Open-source clouds are built by relying on one or more datacenters. In most cases hardware resources are virtualized to provide isolation of workloads and to best exploit the infrastructure. According to the specific service delivered to the end user, different layers can be stacked on top of the virtual infrastructure: a virtual machine manager, a development platform, or a specific application middleware.

A broad definition of the phenomenon could be as follows:

"Cloud computing is a utility-oriented and Internet-centric way of delivering IT services on demand. These services cover the entire computing stack: from the hardware infrastructure packaged as a set of virtual machines to software services such as development platforms and distributed applications."

2. cloud reference model

Cloud computing supports any IT service that can be consumed as a utility and delivered through a network, most likely the Internet.

Such characterization includes quite different aspects: infrastructure, development platforms, application, and services.

2.1 Architecture

2.2 Infrastructure / hardware as a service

2.3 Platform as a service

2.4 Software as a service

2.1 Architecture

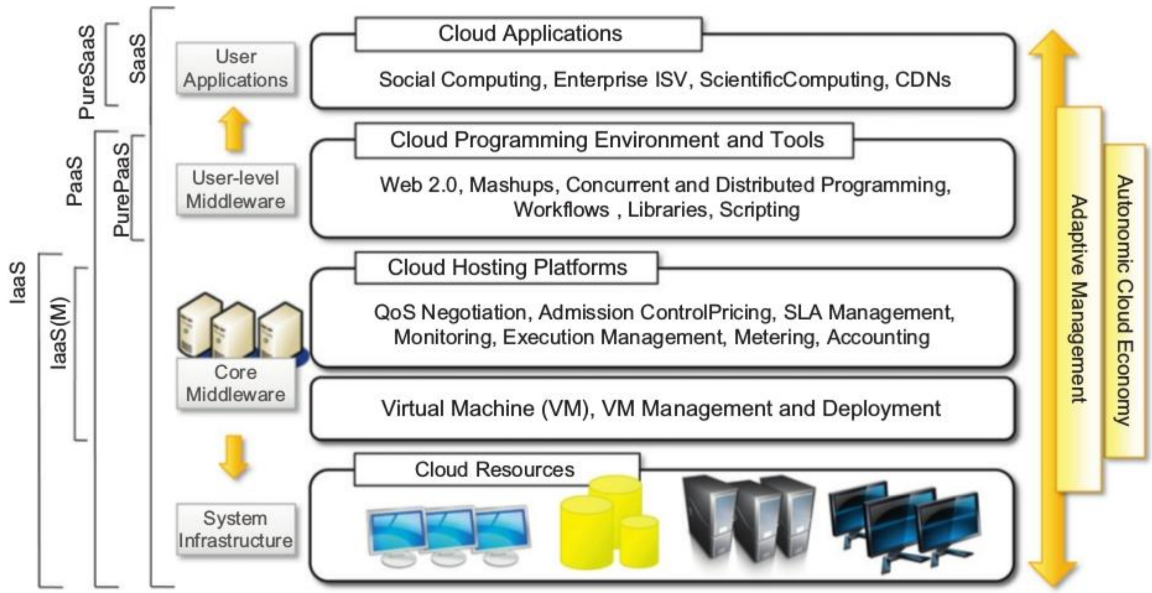


FIGURE 4.1

The cloud computing architecture.

It is possible to organize all the concrete realizations of cloud computing into a layered view covering the entire stack (see Figure 4.1), from hardware appliances to software systems.
Cloud infrastructure can be heterogeneous in nature because a variety of resources, such as clusters and even networked PCs, can be used to build it.

- The **physical infrastructure** is managed by the **core middleware**, the objectives of which are to provide an appropriate **runtime environment** for applications and to best utilize resources.
- At the bottom of the stack, **virtualization technologies** are used to guarantee runtime environment customization, application isolation, sandboxing, and quality of service. **Hardware virtualization** is most used at this level. **Hypervisors** manage the pool of resources and expose the distributed infrastructure as a collection of virtual machines. By using virtual machine technology, it is possible to finely partition the hardware resources such as CPU and memory and to virtualize specific devices, thus meeting the requirements of users and applications. This solution is generally paired with storage and network virtualization strategies, which allow the infrastructure to be completely virtualized and controlled.
- **Infrastructure management** is the key function of core middleware, which supports capabilities such as negotiation of the quality of service, admission control, execution management and monitoring, accounting, and billing. The combination of **cloud hosting**

platforms and resources is generally classified as an **Infrastructure- as-a-Service (IaaS)** solution.

- We can organize the different examples of IaaS into two categories: Some of them provide both the management layer and the physical infrastructure; others provide only the management layer (IaaS (M)).
- **User-level middleware:** The range of tools include Web-based interfaces, command-line tools, and frameworks for concurrent and distributed programming. In this scenario, users develop their applications specifically for the cloud by using the API exposed at the user-level middleware. For this reason, this approach is also known as **Platform-as-a-Service (PaaS)** because the service offered to the user is a **development platform** rather than an infrastructure.
- The top layer of the reference model is **User Application level:** These are referred as **Software-as-a-Service (SaaS).** In most cases these are Web-based applications that rely on the cloud to provide service to end users.
- The horsepower of the cloud provided by IaaS and PaaS solutions allows independent software vendors to deliver their application services over the Internet.

Table 4.1 summarizes the characteristics of the three major categories used to classify cloud computing solutions. In the following section, we briefly discuss these characteristics along with some references to practical implementations.

Table 4.1 Cloud Computing Services Classification

Category	Characteristics	Product Type	Vendors and Products
SaaS	Customers are provided with applications that are accessible anytime and from anywhere.	Web applications and services (Web 2.0)	SalesForce.com (CRM) Clarizen.com (project management) Google Apps
PaaS	Customers are provided with a platform for developing applications hosted in the cloud.	Programming APIs and frameworks Deployment systems	Google AppEngine Microsoft Azure Manjrasoft Aneka Data Synapse
IaaS/HaaS	Customers are provided with virtualized hardware and storage on top of which they can build their infrastructure.	Virtual machine management infrastructure Storage management Network management	Amazon EC2 and S3 GoGrid Nirvanix

2.2 IaaS (Infrastructure / Hardware as a Service)

Infrastructure / Hardware-as-a-Service (IaaS / HaaS) solutions are the most popular and developed market segment of cloud computing. They **deliver customizable infrastructure on demand**.

The available options within the IaaS offering umbrella range from single servers to entire infrastructures, including network devices, load balancers, and database and Web servers.

The main technology used to deliver and implement these solutions is **hardware virtualization**: one or more virtual machines opportunely configured and interconnected define the distributed system on top of which applications are installed and deployed. Virtual machines also constitute the atomic components that are deployed and priced according to the specific features of the virtual hardware: memory, number of processors, and disk storage.

From the perspective of the customer, it reduces the administration and maintenance cost as well as the capital costs allocated to purchase hardware.

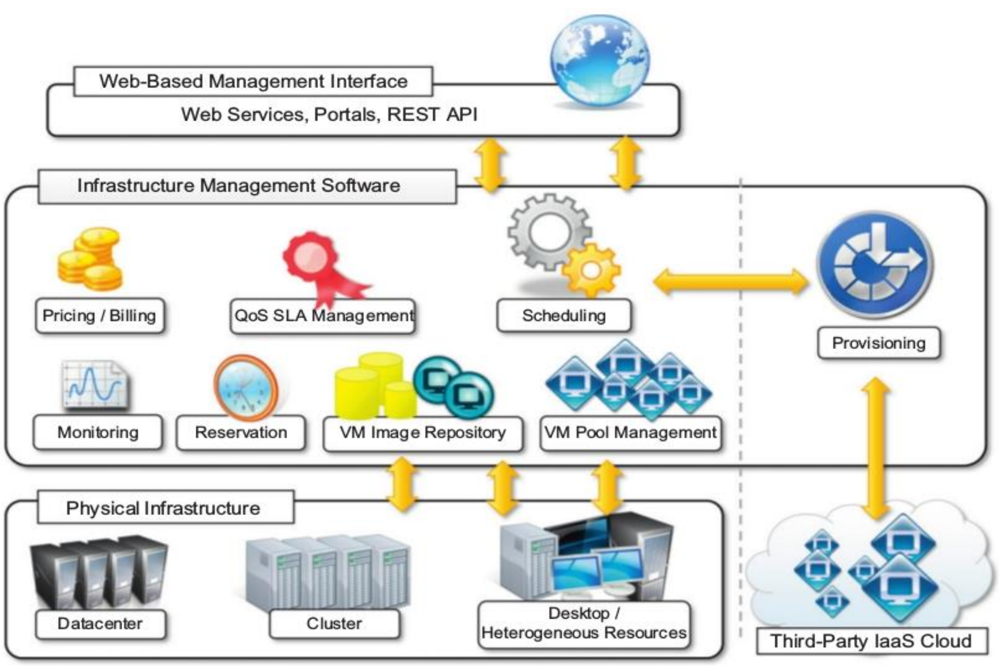


FIGURE 4.2

Infrastructure-as-a-Service reference implementation.

Figure 4.2 provides an overall view of the components forming an Infrastructure-as-a-Service solution. It is possible to distinguish three principal layers: the physical infrastructure, the software management infrastructure, and the user interface.

- At the top layer the **user interface (Web based Management Interface):** provides access to the services exposed by the software management infrastructure. Such an **interface is based** on **Web 2.0 technologies: Web services, RESTful APIs, and mashups**. These technologies allow either applications or final users to access the services exposed by the underlying infrastructure. Web 2.0 applications allow developing full- featured management consoles completely hosted in a browser or a Web page. Web services and RESTful APIs allow programs to interact with the service without human intervention, thus providing complete integration within a software system.

- The core features of an IaaS solution are implemented in the **infrastructure management software layer:** In particular, management of the virtual machines is the most important function performed by this layer. A central role is played by the scheduler, which oversees **allocating the execution of virtual machine instances**. The scheduler interacts with the other components that perform a variety of tasks:
  - The **pricing and billing** component takes care of the cost of executing each virtual machine instance and maintains data that will be used to charge the user.
  - The **monitoring component** tracks the execution of each virtual machine instance and maintains data required for reporting and analyzing the performance of the system.
  - The **reservation component** stores the information of all the virtual machine instances that have been executed or that will be executed in the future.
  - If support for **QoS-based** execution is provided, a QoS/SLA management component will maintain a repository of all the SLAs made with the users; together with the monitoring component, this component is used to ensure that a given virtual machine instance is executed with the desired **quality of service**.
  - The **VM Image repository** component provides a catalog of virtual machine images that users can use to **create virtual instances**. Some implementations also allow users to upload their specific virtual machine images.
  - A **VM Pool Management** component is responsible for keeping track of all the live instances.
  - Finally, if the system supports the integration of additional resources belonging to a third-party IaaS provider, a **provisioning component** interacts with the scheduler to provide a **virtual machine instance** that is **external** to the local physical infrastructure directly managed by the pool.
- The bottom layer is composed of the **physical infrastructure**, on top of which the management layer operates. As previously discussed, the infrastructure can be of different types; the specific infrastructure used depends on the specific use of the cloud. A cloud infrastructure developed in house, in a small or medium-sized enterprise or within a university department, will most likely rely on a cluster. At the bottom of the scale, it is also possible to consider a heterogeneous environment where different types of resources—PCs, workstations, and clusters—can be aggregated.

2.3 PaaS (Platform as a service)

Platform-as-a-Service (PaaS) solutions provide a **development and deployment platform for running applications in the cloud**. They constitute the middleware on top of which applications are built. A general overview of the features characterizing the PaaS approach is given in Figure 4.3. Application management is the core functionality of the middleware.

PaaS implementations provide **applications with a runtime environment** and do not expose any service for managing the underlying infrastructure. They **automate** the process of **deploying** applications to the infrastructure, **configuring** application components, **provisioning**, and configuring supporting technologies such as **load balancers** and **databases**, and **managing system** change based on **policies** set by the **user**.

The **core middleware** oversees managing the resources and scaling applications on demand or automatically, according to the commitments made with users.
From a **user point of view**, the **core middleware exposes interfaces that allow programming and deploying applications on the cloud**. These can be in the **form of a Web-based interface** or in the form of **programming APIs and libraries**.

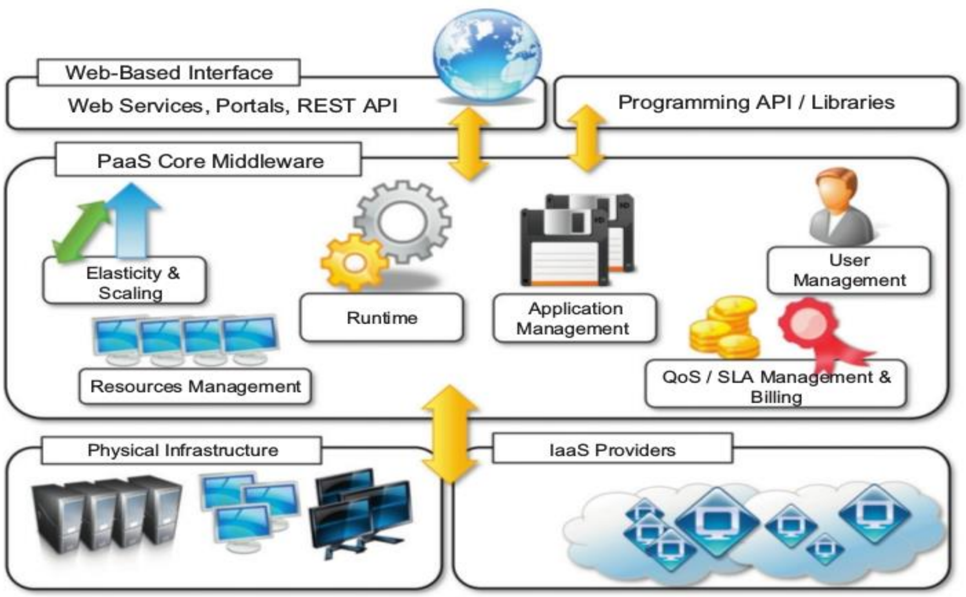


FIGURE 4.3
The Platform-as-a-Service reference model.

PaaS solutions can offer middleware for developing applications together with the infrastructure or simply provide users with the software that is installed on the user premises.
In the **first case**, the PaaS provider also owns large datacenters where applications are executed.
In the **second case**, referred as Pure PaaS, the middleware constitutes the core value of the offering.

Table 4.2 provides a classification of the most popular PaaS implementations. It is possible to organize the various solutions into three wide categories: PaaS-I, PaaS-II, and PaaS-III.

Table 4.2 Platform-as-a-Service Offering Classification

Category	Description	Product Type	Vendors and Products
PaaS-I	Runtime environment with Web-hosted application development platform. Rapid application prototyping.	Middleware + Infrastructure Middleware + Infrastructure	Force.com Longjump
PaaS-II	Runtime environment for scaling Web applications. The runtime could be enhanced by additional components that provide scaling capabilities.	Middleware + Infrastructure Middleware Middleware + Infrastructure Middleware + Infrastructure Middleware + Infrastructure Middleware	Google AppEngine AppScale Heroku Engine Yard Joyent Smart Platform GigaSpaces XAP
PaaS-III	Middleware and programming model for developing distributed applications in the cloud.	Middleware + Infrastructure Middleware Middleware Middleware Middleware Middleware	Microsoft Azure DataSynapse Cloud IQ Manjrasof Aneka Apprenda SaaSGrid GigaSpaces DataGrid

As noted by Sam Charrington, product manager at **Appistry.com**, there are some essential characteristics that identify a PaaS solution:

1. Runtime framework - This framework represents the "software stack" of the PaaS model. The runtime framework **executes end-user code** according to the policies set by the user and the provider.

2. Abstraction - PaaS, the focus is on the **applications the cloud must support**. PaaS solutions offer a way to **deploy and manage applications on the cloud** rather than a bunch of virtual machines on top of which the IT infrastructure is built and configured.

3. Automation - **scaling** them by provisioning **additional resources when needed**. This process is performed automatically and according to the SLA made between the customers and the provider.

4. Cloud services - PaaS offerings provide developers and architects with services and APIs, helping them to simplify the creation and delivery of elastic and highly available cloud applications.

2.4 Software as a service

Software-as-a-Service (SaaS) is a **software delivery model** that provides access to applications through the **Internet as a Web-based service**.

It provides a means to **free users from complex hardware and software management** by offloading such tasks to third parties, which build applications accessible to multiple users through a Web browser.

In this scenario, customers neither need install anything on their premises nor have to pay considerable up-front costs to purchase the software and the required licenses.

The SaaS model is appealing for applications serving a wide range of users and that can be adapted to specific needs with little further customization. This requirement characterizes **SaaS as a "one-to- many" software delivery model, whereby an application is shared across multiple users.**

This is the case of CRM 3 and ERP 4 applications that constitute common needs for almost all enterprises, from small to medium-sized and large business. Every enterprise will have the same requirements for the basic features concerning CRM and ERP; different needs can be satisfied with further customization.

ASPs (application service providers) has some of the core characteristics of SaaS:
1. The product sold to customer is application access.
2. The application is centrally managed.
3. The service delivered is one-to-many.
4. The service delivered is an integrated solution delivered on the contract, which means provided as promised.

ASPs provide access to packaged software solutions that addressed the needs of a variety of customers.

The SaaS approach introduces a more flexible way of delivering application services that are fully customizable by the user by integrating new services, injecting their own components, and designing the application and information workflows.

The benefits delivered are the following:
1 Software cost reduction and total cost of ownership (TCO) were paramount (Highly Important)
2 Service-level improvements
3 Rapid implementation
4 Standalone and configurable applications
5 Rudimentary (Simple) application and data integration
6 Subscription and pay-as-you-go (PAYG) pricing

3. Types of Clouds

A more useful classification is given according to the administrative domain of a cloud. It is then possible to differentiate four different types of cloud:

1. Public clouds. The cloud is open to the wider public.

2. Private clouds. The cloud is implemented within the private premises of an **institution** and generally made **accessible to the members of the institution or a subset** of them.

3. Hybrid or Heterogeneous clouds. The cloud is a combination of the two previous (Public + Private) solutions and most likely identifies a private cloud that has been augmented with resources or services hosted in a public cloud.

4. Community clouds. The cloud is characterized by a multi-administrative domain involving different deployment models (public, private, and hybrid), and it is specifically designed to address the needs of a specific industry.

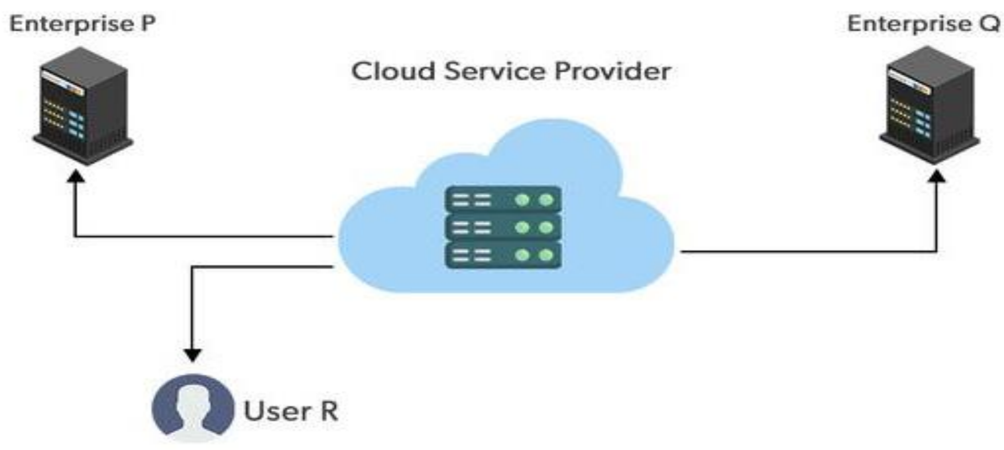
3.1 Public clouds

Public clouds are a realization of the canonical view of cloud computing in which the services offered are made available to anyone, from anywhere, and at any time through the Internet.

Public clouds are managed by third parties which provide cloud services over the internet to the public, these services are available as pay-as-you-go billing models.

Public clouds offer solutions for minimizing IT infrastructure costs and become a good option for handling peak loads on the local infrastructure. Public clouds are the go-to option for small enterprises, which are able to start their businesses without large upfront investments by completely relying on public infrastructure for their IT needs.

The fundamental characteristics of public clouds are multitenancy. A public cloud is meant to serve multiple users, not a single customer. A user requires a virtual computing environment that is separated, and most likely isolated, from other users.



Public cloud

A public cloud can offer any kind of service: infrastructure, platform, or applications.

For example:

- **Amazon EC2** is a public cloud that provides infrastructure as a service.
- **Google AppEngine** is a public cloud that provides an application development platform as a service and
- **SalesForce.com** is a public cloud that provides software as a service.

3.2 Private clouds

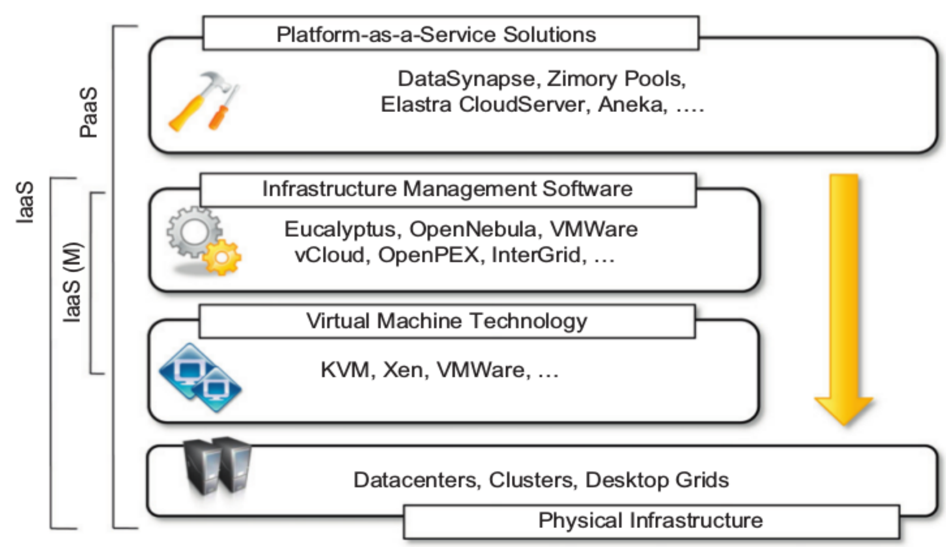


FIGURE 4.4

Private clouds hardware and software stack.

Figure 4.4 provides a comprehensive view of the solutions together with some reference to the most popular software used to deploy private clouds.

At the bottom layer of the software stack, virtual machine technologies such as Xen, KVM, and VMware serve as the foundations of the cloud.

Virtual machine management technologies such as VMware vCloud, Eucalyptus, and Open Nebula can be used to control the virtual infrastructure.

Private clouds are virtual distributed systems that rely on a private infrastructure and provide internal users with dynamic provisioning of computing resources. Instead of a pay-as-you-go model as in public clouds, there could be other schemes in place, considering the usage of the cloud and proportionally billing the different departments or sections of an enterprise.

Key advantages of using a private cloud computing infrastructure:

1. **Customer information protection**: In the private cloud security concerns are less since customer data and other sensitive information do not flow out of private infrastructure.
2. **Infrastructure ensuring Service Level Agreements (SLAs):** Private cloud provides specific operations such as appropriate clustering, data replication, system monitoring, and maintenance, and disaster recovery, and other uptime services.
3. **Compliance with standard procedures and operations:** Specific procedures have to be put in place when deploying and executing applications according to third-party compliance standards. This is not possible in the case of the public cloud.

3.3 Hybrid clouds / Heterogeneous clouds

A hybrid cloud is a heterogeneous distributed system formed by combining facilities of public cloud and private cloud.

A major drawback of private deployments is the inability to scale on-demand and efficiently address peak loads. Here public clouds are needed. Hence, a hybrid cloud takes advantage of both public and private clouds.

Figure 4.5 provides a general overview of a hybrid cloud: It is a heterogeneous distributed system resulting from a private cloud that **integrates additional services or resources from one or more public and private clouds**. For this reason, they are also called **heterogeneous clouds.**

As depicted in the diagram, dynamic provisioning is a fundamental component in this scenario. Hybrid clouds address scalability issues by leveraging external resources for exceeding capacity demand. These resources or services are temporarily leased for the time required and then released. This practice is also known as cloud-bursting.

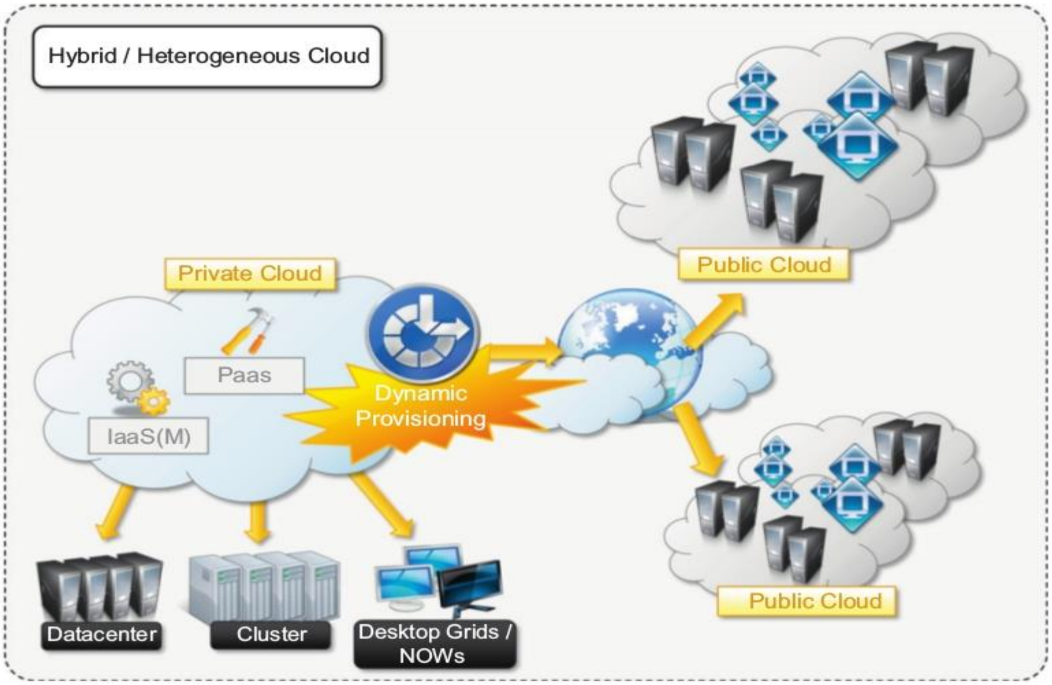


FIGURE 4.5

Hybrid/heterogeneous cloud overview.

3.4 Community clouds

Community clouds are distributed systems created by integrating the services of different clouds to address the specific needs of an industry, a community, or a business sector.

The National Institute of Standards and Technologies (NIST) characterizes community clouds as follows:
"The infrastructure is shared by several organizations and supports a specific community that has shared concerns (e.g., mission, security requirements, policy, and compliance considerations). It may be managed by the organizations or a third party and may exist on premise or off premise."

Or

In the community cloud, the infrastructure is shared between organizations that have shared concerns or tasks. The cloud may be managed by an organization or a third party.

Figure 4.6 provides a general view of the usage scenario of community clouds, together with reference architecture. The users of a specific community cloud fall into a well-identified community, sharing the same concerns or needs; they can be government bodies, industries, or even simple users, but all of them focus on the same issues for their interaction with the cloud.

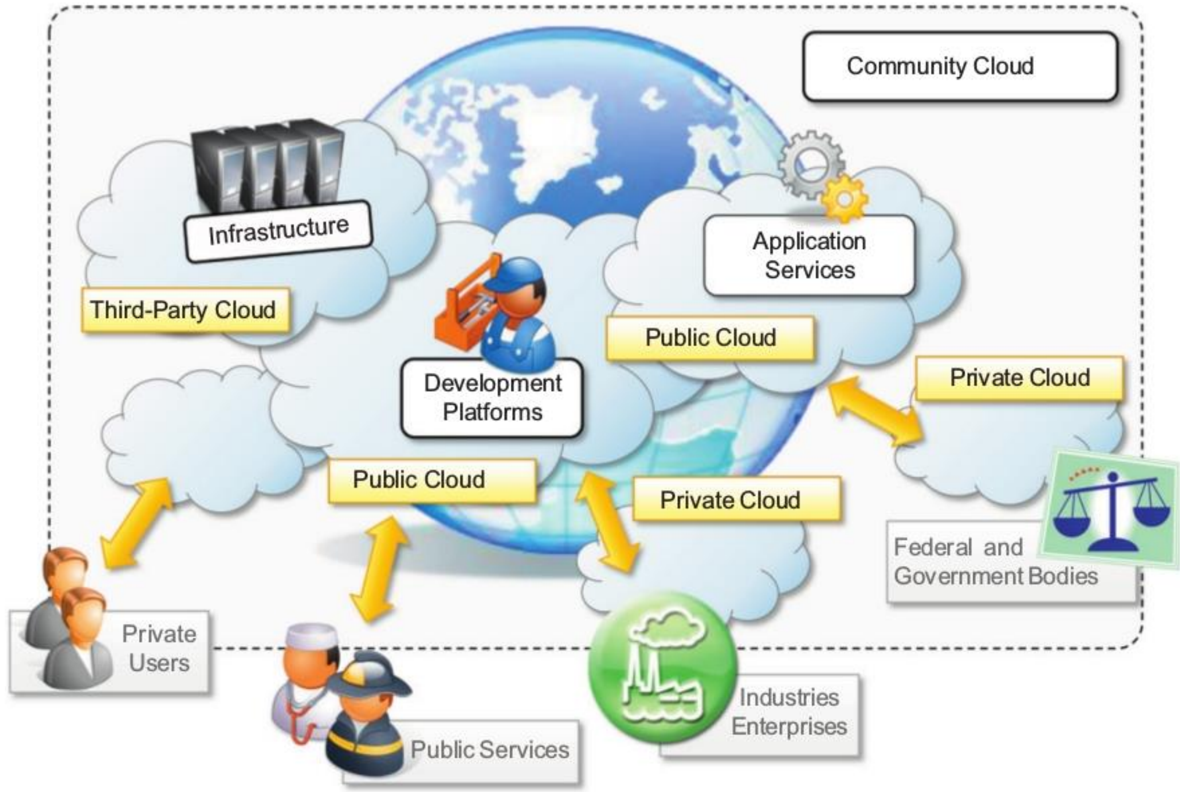


FIGURE 4.6

A community cloud.

Candidate sectors for community clouds are as follows:

1. Media industry - looking for low-cost, agile, and simple solutions to improve the efficiency of content production.

2. Healthcare industry - n the healthcare industry community clouds are used to share information and knowledge on the global level with sensitive data in the private infrastructure.

3. Energy and other core industries - In these sectors, community clouds can bundle the comprehensive set of solutions that together vertically address management, deployment, and orchestration of services and operations.

4. Public sector - Legal and political restrictions in the public sector can limit the adoption of public cloud offerings. Moreover, governmental processes involve several institutions and agencies and are aimed at providing strategic solutions at local, national, and international administrative levels.

5. Scientific research - In this organization with common interests in science share a large, distributed infrastructure for scientific computing.

The benefits of these community clouds are the following:

1. **Openness.** By removing the dependency on cloud vendors, community clouds are open systems in which fair competition between different solutions can happen.
2. **Community.** Being based on a collective that provides resources and services, the infrastructure turns out to be more scalable because the system can grow simply by expanding its user base.
3. **Graceful failures.** Since there is no single provider or vendor in control of the infrastructure, there is no single point of failure.
4. **Convenience and control.** Within a community cloud there is no conflict between convenience and control because the cloud is shared and owned by the community, which makes all the decisions through a collective democratic process.
5. **Environmental sustainability.** The community cloud is supposed to have a smaller carbon footprint because it harnesses underutilized resources. Moreover, these clouds tend to be more organic by growing and shrinking in a symbiotic relationship to support the demand of the community, which in turn sustains it.

4. Economics of the cloud

The main drivers of cloud computing are economy of scale and simplicity of software delivery and its operation. In fact, the **biggest benefit** of this phenomenon is **financial: the pay-as-you-go** model offered by cloud providers. In particular, cloud computing allows:

1. **Reducing** the capital costs associated to the IT infrastructure
2. **Eliminating** the depreciation or lifetime costs associated with IT capital assets
3. **Replacing** software licensing with subscriptions
4. **Cutting** the maintenance and administrative costs of IT resources.

A **capital** cost is the cost occurred in purchasing an asset that is useful in the production of goods or the rendering of services. Capital costs are one-time expenses that are generally paid-up front and that will contribute over the long term to generate profit.

IT resources constitute a capital cost for any kind of enterprise. It is good practice to try to keep capital costs low because they introduce expenses that will generate profit over time; more than that, since they are associated with material things, they are subject to depreciation over time, which in the end reduces the profit of the enterprise because such costs are directly subtracted from the enterprise revenues.

One of the advantages introduced by the cloud computing model is that it shifts the capital costs previously allocated to the purchase of hardware and software into operational costs inducted by renting the infrastructure and paying subscriptions for the use of software. These costs can be better controlled according to the business needs and prosperity of the enterprise. Cloud computing also introduces reductions in administrative and maintenance costs. That is, there is no or limited need for having administrative staff take care of the management of the cloud infrastructure.

In terms of the pricing models introduced by cloud computing, we can distinguish three different strategies that are adopted by the providers:

1. Tiered pricing - In this model, cloud services are offered in several tiers, each of which offers a fixed computing specification and Service Level Agreement (SLA) at a specific price per unit of time. This model is used by Amazon for pricing the EC2 service.

2. Per-unit pricing - This model is more suitable to cases where the principal source of revenue for the cloud provider is determined in terms of units of specific services, such as **data transfer and memory allocation**. In this scenario customers can configure their systems more efficiently according to the application needs. This model is used, for example, by GoGrid, which makes customers pay according to **RAM/hour units** for the servers deployed in the GoGrid cloud.

3. Subscription-based pricing - This is the model used mostly by SaaS providers in which users pay a periodic subscription fee for use of the software or the specific component services that are integrated in their applications.

5. Open Challenges

Cloud computing presents many challenges for industry and academia. There is a significant amount of work in academia focused on defining the challenges brought by this phenomenon.

In this section, we highlight the most important ones.

1 Cloud definition

2 Cloud interoperability and standards

3 Scalability and fault tolerance

4 Security, trust, and privacy

5 Organizational aspects

1 Cloud definition

There have been several attempts made to define cloud computing and to provide a classification of all the services and technologies identified as such.

NSIT characterizes cloud computing as on-demand **self-service**, **broad network access, resource- pooling, rapid elasticity, and measured service**; classifies services as **SaaS, PaaS, and IaaS**; and categorizes deployment models as **public, private, community, and hybrid clouds**.

Alternative taxonomies for cloud services. David Linthicum, founder of Blue Mountains Labs, provides a more detailed classification, which comprehends 10 different classes and better suits the vision of cloud computing within the enterprise.

These characterizations and taxonomies reflect what is meant by cloud computing at the present time but being in its infancy the phenomenon is constantly evolving, and the same will happen to the attempts to capture the real nature of cloud computing.

2 Cloud interoperability and standards

To fully realize this goal, introducing standards and allowing interoperability between solutions offered by different vendors are objectives of fundamental importance. Vendor lock-in constitutes one of the major strategic barriers against the seamless adoption of cloud computing at all stages. The presence of standards that are implemented and adopted in the cloud computing community could give room for interoperability and then lessen the risks resulting from vendor lock-in.

The first steps toward a standardization process have been made, and a few organizations, such as the Cloud Computing Interoperability Forum (CCIF), the Open Cloud Consortium, and the DMTF Cloud Standards Incubator, are leading the path.

Another interesting initiative is the Open Cloud Manifesto, which embodies the point of view of various stakeholders on the benefits of open standards in the field.

The Open Virtualization Format (OVF) is an attempt to provide a common format for storing the information and metadata describing a virtual machine image. Even though the OVF provides a full specification for packaging and distributing virtual machine images in completely platform- independent fashion, it is supported by few vendors that use it to import static virtual machine images.

3 Scalability and fault tolerance

The ability to scale on demand constitutes one of the most attractive features of cloud computing. Clouds allow scaling beyond the limits of the existing in-house IT resources, whether they are infrastructure (compute and storage) or applications services. To implement such a capability, the cloud middleware has to be designed with the principle of scalability along different dimensions in mind— for example, **performance, size, and load.**

The cloud middleware manages a huge number of resource and users, which rely on the cloud to obtain the horsepower. In this scenario, the ability to tolerate failure becomes fundamental, sometimes even more important than providing an extremely efficient and optimized system. Hence, the challenge in this case is designing highly scalable and fault-tolerant systems that are easy to manage and at the same time provide competitive performance.

4 Security, trust, and privacy

Security, trust, and privacy issues are major obstacles for massive adoption of cloud computing. The traditional cryptographic technologies are used to prevent data tampering and access to sensitive information. The massive use of virtualization technologies exposes the existing system to new threats, which previously were not considered applicable.

Information can be stored within a cloud storage facility using the most advanced technology in cryptography to protect data and then be considered safe from any attempt to access it without the required permissions.

The lack of control over data and processes also poses severe problems for the trust we give to the cloud service provider and the level of privacy we want to have for our data.

5 Organizational aspects

More precisely, **storage, compute power, network infrastructure, and applications are delivered as metered services over the Internet**. This introduces a billing model that is new within typical enterprise IT departments, which requires a certain level of cultural and organizational process maturity.

In particular, the following questions must be considered:

1. What is the new role of the IT department in an enterprise that completely or significantly relies on the cloud?
2. How will the compliance department perform its activity when there is a considerable lack of

control over application workflows?

3. What are the implications (political, legal, etc.) for organizations that lose control over some aspects of their services?

4. What will be the perception of the end users of such services?

From an organizational point of view, the lack of control over the management of data and processes poses not only security threats but also new problems that previously did not exist.