Virtualization

Virtualization technology is one of the fundamental components of cloud computing, especially in regard to infrastructure-based services. Virtualization allows the creation of a secure, customizable, and isolated execution environment for running applications, even if they are untrusted, without affecting other users' applications. The basis of this technology is the ability of a computer program—or a combination of software and hardware—to emulate an executing environment separate from the one that hosts such programs.

Introduction

Virtualization is a large umbrella of technologies and concepts that are meant to provide an abstract environment—whether virtual hardware or an operating system—to run applications. The term virtualization is often synonymous with hardware virtualization, which plays a fundamental role in efficiently delivering Infrastructure-as-a-Service (IaaS) solutions for cloud computing.
Virtualization technologies have gained renewed interested recently due to the confluence of several phenomena:

- <u>Increased performance and computing capacity.</u>

  The high-end side of the PC market, where supercomputers can provide immense compute power that can accommodate the execution of hundreds or thousands of virtual machines.
- <u>Underutilized hardware and software resources.</u>

  Hardware and software underutilization is occurring due to (1) increased performance and computing capacity, and (2) the effect of limited or sporadic use of resources.
  Computers today are so powerful that in most cases only a fraction of their capacity is used by an application or the system. Using these resources for other purposes after hours could improve the efficiency of the IT infrastructure.
- <u>Lack of space.</u>

  Companies such as Google and Microsoft expand their infrastructures by building data centers as large as football fields that are able to host thousands of nodes. Although this is viable for IT giants, in most cases enterprises cannot afford to build another data center to accommodate additional resource capacity. This condition, along with hardware underutilization, has led to the diffusion of a technique called server consolidation
- <u>Greening initiatives.</u>

  Maintaining a data center operation not only involves keeping servers on, but a great deal of energy is also consumed in keeping them cool. Infrastructures for cooling have a significant impact on the carbon footprint of a data center. Hence, reducing the number of servers through server consolidation will definitely reduce the impact of cooling and power consumption of a data center. Virtualization technologies can provide an efficient way of consolidating servers.
- <u>Rise of administrative costs.</u>

  The increased demand for additional capacity, which translates into more servers in a data center, is also responsible for a significant increment in administrative costs. Computers—in particular, servers—do not operate all on their own, but they require care and feeding from system administrators.
  These are labor-intensive operations, and the higher the number of servers that have to be

managed, the higher the administrative costs. Virtualization can help reduce the number of required servers for a given workload, thus reducing the cost of the administrative personnel.

Characteristics of virtualized environments

Virtualization is a broad concept that refers to the creation of a virtual version of something, whether hardware, a software environment, storage, or a network. In a virtualized environment there are three major components: guest, host, and virtualization layer. The guest represents the system component that interacts with the virtualization layer rather than with the host, as would normally happen. The host represents the original environment where the guest is supposed to be managed. The virtualization layer is responsible for recreating the same or a different environment where the guest will operate (see Figure 3.1).

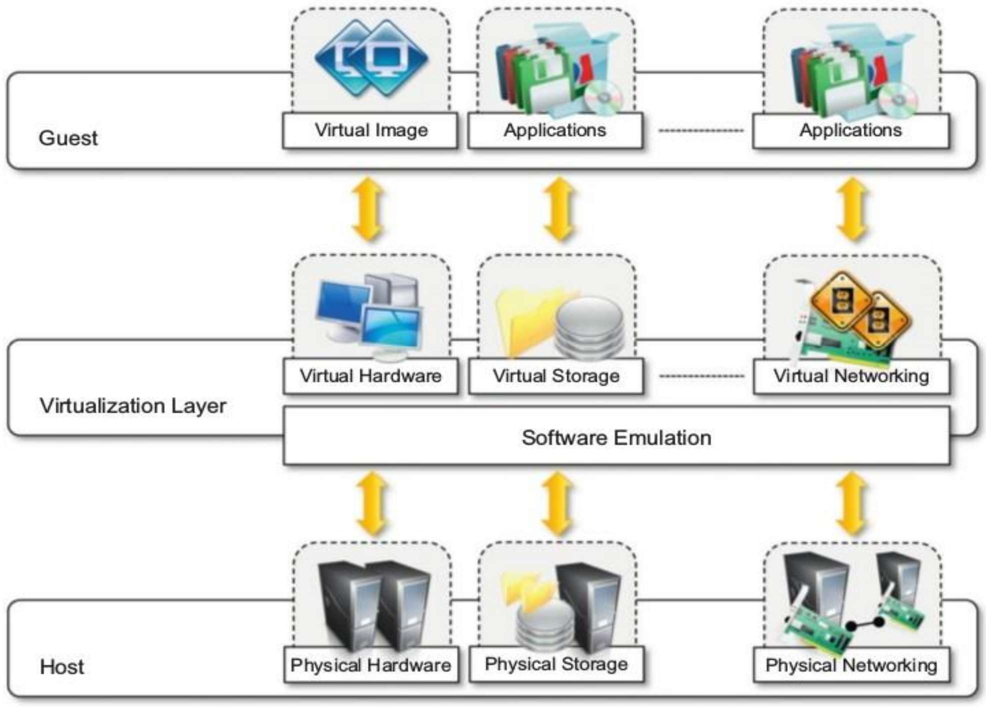

FIGURE 3.1

The virtualization reference model.

The characteristics of virtualized solutions are:
1 Increased security
2 Managed execution
3 Portability

1. Increased security

The virtual machine represents an emulated environment in which the guest is executed. All the operations of the guest are generally performed against the virtual machine, which then translates and applies them to the host. This level of indirection allows the virtual machine manager to control and filter the activity of the guest, thus preventing some harmful operations from being performed. For example, applets downloaded from the Internet run in a sandboxed 3 version of the Java Virtual Machine (JVM), which provides them with limited access to the hosting operating system resources.

Both the JVM and the .NET runtime provide extensive security policies for customizing the execution environment of applications.

2 Managed execution.
Virtualization of the execution environment not only allows increased security, but a wider range of features also can be implemented. In particular, sharing, aggregation, emulation, and isolation are the most relevant features (see Figure 3.2).

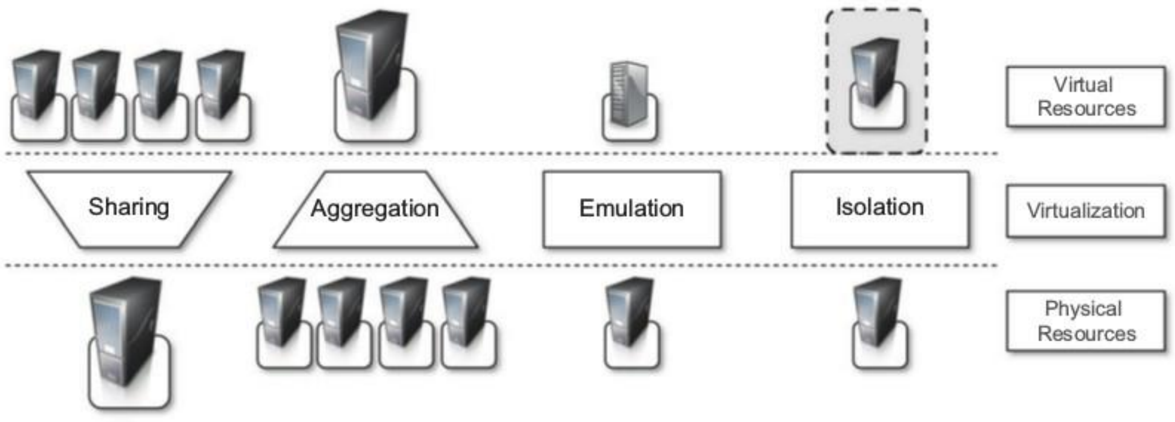

FIGURE 3.2

Functions enabled by managed execution.

Sharing. Virtualization allows the creation of a separate computing environments within the same host. In this way it is possible to fully exploit the capabilities of a powerful guest, which would otherwise be underutilized.
Aggregation. Not only is it possible to share physical resource among several guests, but virtualization also allows aggregation, which is the opposite process. A group of separate hosts can be tied together and represented to guests as a single virtual host.
Emulation. Guest programs are executed within an environment that is controlled by the virtualization layer, which ultimately is a program. This allows for controlling and tuning the environment that is exposed to guests. For instance, a completely different environment with respect to the host can be emulated, thus allowing the execution of guest programs requiring specific characteristics that are not present in the physical host.
Isolation. Virtualization allows providing guests—whether they are operating systems, applications, or other entities—with a completely separate environment, in which they are executed. The guest program performs its activity by interacting with an abstraction layer, which provides access to the underlying resources.

3 Portability
The concept of portability applies in different ways according to the specific type of virtualization considered. In the case of a hardware virtualization solution, the guest is packaged into a virtual image that, in most cases, can be safely moved and executed on top of different virtual machines.
In the case of programming-level virtualization, as implemented by the JVM or the .NET runtime, the binary code representing application components (jars or assemblies) can be run without any

recompilation on any implementation of the corresponding virtual machine. This makes the application development cycle more flexible and application deployment very straightforward: One version of the application, in most cases, is able to run on different platforms with no changes.

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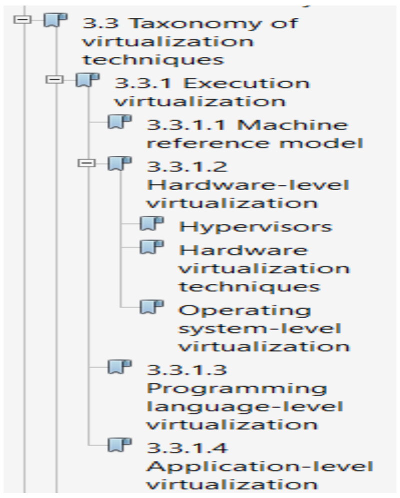

- 3.3 Taxonomy of virtualization techniques
  - 3.3.1 Execution virtualization
    - 3.3.1.1 Machine reference model
    - 3.3.1.2 Hardware-level virtualization
      - Hypervisors
      - Hardware virtualization techniques
      - Operating system-level virtualization
    - 3.3.1.3 Programming language-level virtualization
    - 3.3.1.4 Application-level virtualization

Taxonomy of virtualization techniques

Virtualization covers a wide range of emulation techniques that are applied to different areas of computing. A classification of these techniques helps us better understand their characteristics and use (see Figure 3.3).
The first classification discriminates against the service or entity that is being emulated.

Virtualization is mainly used to emulate execution environments, storage, and networks. Among these categories, execution virtualization constitutes the oldest, most popular, and most developed area. Therefore, it deserves major investigation and a further categorization.

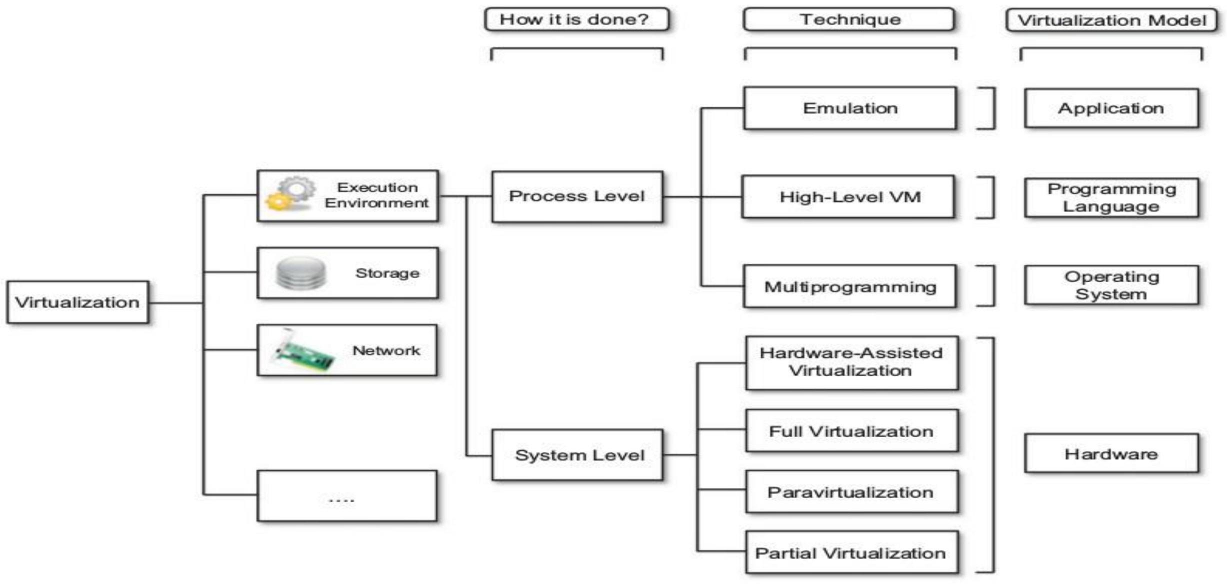

FIGURE 3.3
A taxonomy of virtualization techniques.

1. Execution virtualization

Execution virtualization includes all techniques that aim to emulate an execution environment that is separate from the one hosting the virtualization layer. All these techniques concentrate

their interest on providing support for the execution of programs, whether these are the operating system, a binary specification of a program compiled against an abstract machine model, or an application

1.1 Machine reference model

Modern computing systems can be expressed in terms of the reference model described in Figure 3.4. At the bottom layer, the model for the hardware is expressed in terms of the Instruction Set Architecture (ISA), which defines the instruction set for the processor, registers, memory, and interrupt management. ISA is the interface between hardware and software, and it is important to the operating system (OS) developer (System ISA) and developers of applications that directly manage the underlying hardware (User ISA). The application binary interface (ABI) separates the operating system layer from the applications and libraries, which are managed by the OS. ABI covers details such as low-level data types, alignment, and call conventions and defines a format for executable programs.

The highest level of abstraction is represented by the application programming interface (API), which interfaces applications to libraries and/or the underlying operating system.

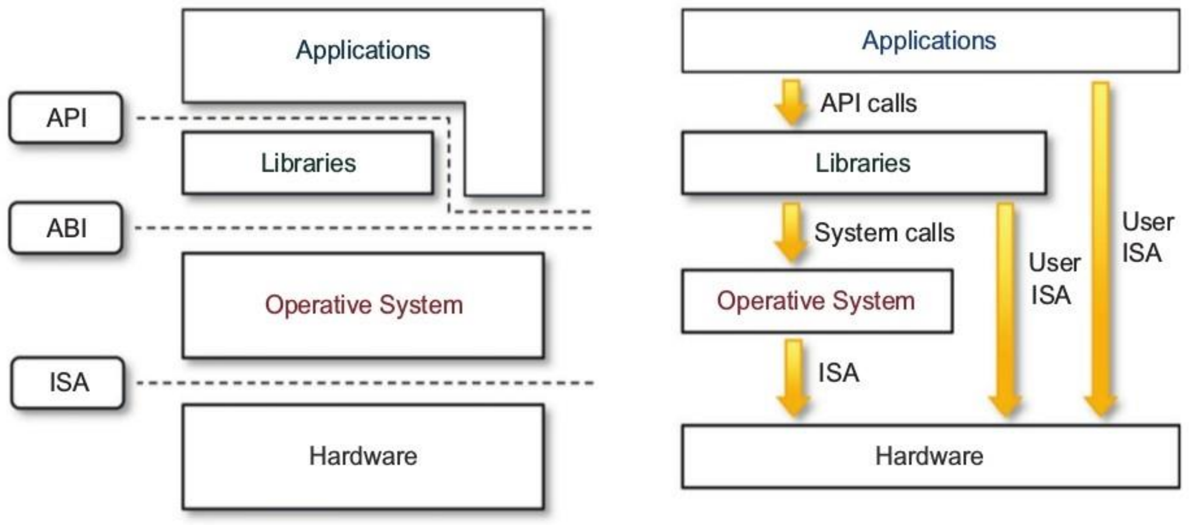

FIGURE 3.4

A machine reference model.

For this purpose, the instruction set exposed by the hardware has been divided into different security classes that define who can operate with them. The first distinction can be made between privileged and nonprivileged instructions. Nonprivileged instructions are those instructions that can be used without interfering with other tasks because they do not access shared resources. This category contains, for example, all the floating, fixed-point, and arithmetic instructions. Privileged instructions are those that are executed under specific restrictions and are mostly used for sensitive operations, which expose (behavior-sensitive) or modify (control-sensitive) the privileged state.

For instance, a possible implementation features a hierarchy of privileges (see Figure 3.5) in the form of ring-based security: Ring 0, Ring 1, Ring 2, and Ring 3; Ring 0 is in the most privileged level and Ring 3 in the least privileged level. Ring 0 is used by the kernel of the OS, rings 1 and 2 are used by the OS-level services, and Ring 3 is used by the user. Recent systems support only two levels, with Ring 0 for supervisor mode and Ring 3 for user mode.

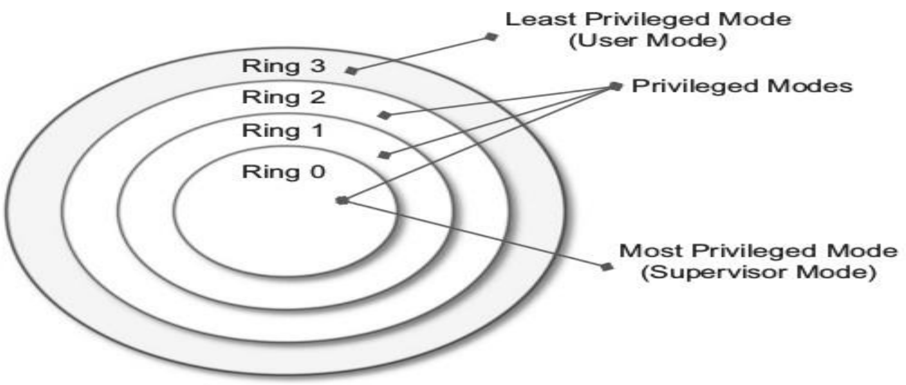
Least Privileged Mode (User Mode)
Ring 3
Ring 2
Ring 1
Ring 0
Privileged Modes
Most Privileged Mode (Supervisor Mode)

FIGURE 3.5

Security rings and privilege modes.

The distinction between user and supervisor mode allows us to understand the role of the hypervisor and why it is called that. Conceptually, the hypervisor runs above the supervisor mode, and from here the prefix hyper- is used. In reality, hypervisors are run in supervisor mode.

1.2 Hardware-level virtualization

Hardware-level virtualization is a virtualization technique that provides an abstract execution environment in terms of computer hardware on top of which a guest operating system can be run. In this model, the guest is represented by the operating system, the host by the physical computer hardware, the virtual machine by its emulation, and the virtual machine manager by the hypervisor (see Figure 3.6). The hypervisor is generally a program or a combination of software and hardware that allows the abstraction of the underlying physical hardware. Hardware-level virtualization is also called system virtualization.

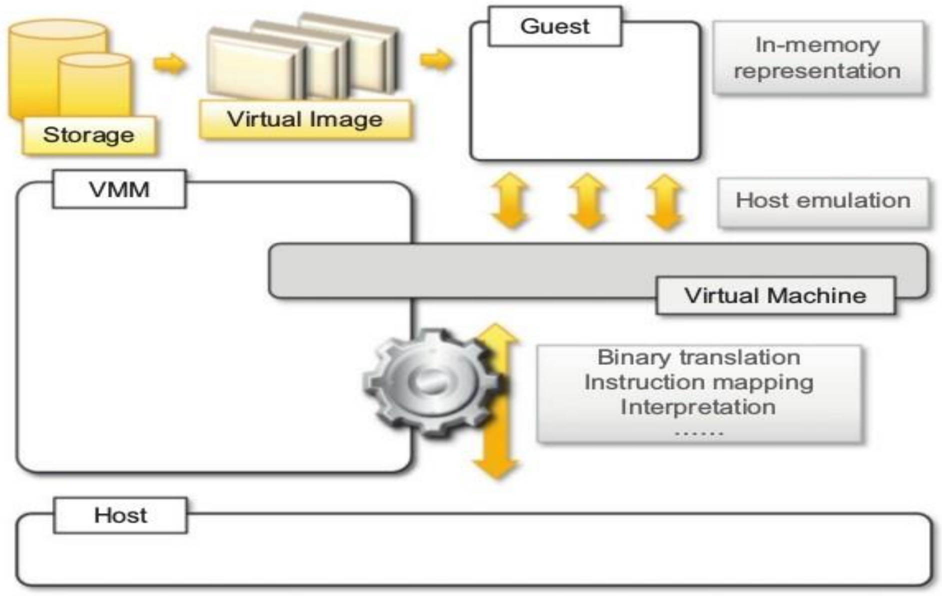

FIGURE 3.6

A hardware virtualization reference model.

a. Hypervisors

A fundamental element of hardware virtualization is the hypervisor, or virtual machine manager (VMM). It recreates a hardware environment in which guest operating systems are installed. There are two major types of hypervisor: Type I and Type II (see Figure 3.7).

Type I hypervisors run directly on top of the hardware. Therefore, they take the place of the operating systems and interact directly with the ISA interface exposed by the underlying hardware, and they emulate this interface in order to allow the management of guest operating systems. This type of hypervisor is also called a native virtual machine since it runs natively on hardware.

Type II hypervisors require the support of an operating system to provide virtualization services. This means that they are programs managed by the operating system, which interact with it through the ABI and emulate the ISA of virtual hardware for guest operating systems. This type of hypervisor is also called a hosted virtual machine since it is hosted within an operating system.

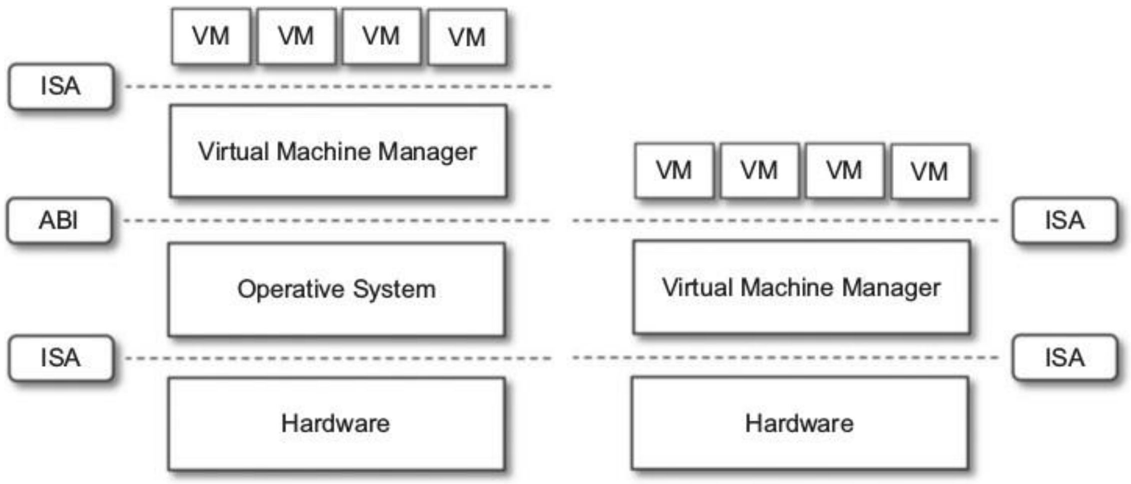

FIGURE 3.7

Hosted (left) and native (right) virtual machines. This figure provides a graphical representation of the two types of hypervisors.

b. Hardware virtualization techniques

Hardware-assisted virtualization. This term refers to a scenario in which the hardware provides architectural support for building a virtual machine manager able to run a guest operating system in complete isolation. This technique was originally introduced in the IBM System/370. At present, examples of hardware-assisted virtualization are the extensions to the x86-64 bit architecture introduced with Intel VT (formerly known as Vanderpool) and AMD V (formerly known as Pacifica). Intel and AMD introduced processor extensions, and a wide range of virtualization solutions took advantage of them: Kernel-based Virtual Machine (KVM), VirtualBox, Xen, VMware, Hyper-V, Sun xVM, Parallels, and others.

Full virtualization. Full virtualization refers to the ability to run a program, most likely an operating system, directly on top of a virtual machine and without any modification, as though it were run on the raw hardware. To make this possible, virtual machine managers are required to provide a complete emulation of the entire underlying hardware. The principal advantage of full virtualization is complete isolation, which leads to enhanced security, ease of emulation of different architectures, and coexistence of different systems on the same platform.

Paravirtualization. Paravirtualization (PV) is an enhancement of virtualization technology in which a guest operating system (guest OS) is modified prior to installation inside a virtual machine (VM) in order to allow all guest OS within the system to share resources and successfully collaborate, rather than attempt to emulate an entire hardware environment. With paravirtualization, virtual machines can be accessed through interfaces that are similar to the underlying hardware. This capacity minimizes overhead and optimizes system performance by supporting the use of VMs that would otherwise be underutilized in conventional or full hardware virtualization. Paravirtualization attempts to resolve issues found in full virtualization. The primary difference between paravirtualization and full virtualization is the ability to make modifications to the guest OS in PV. By granting the guest OS access to the underlying hardware, PV enables communication between the guest OS and the hypervisor, thus improving performance and efficiency within the system.

Partial virtualization. Partial virtualization provides a partial emulation of the underlying hard-ware, thus not allowing the complete execution of the guest operating system in complete isolation. Partial virtualization allows many applications to run transparently, but not all the features of the operating system can be supported.

c. Operating system-level virtualization

Operating system-level virtualization offers the opportunity to create different and separated execu-tion environments for applications that are managed concurrently. Differently from hardware virtua-lization, there is no virtual machine manager or hypervisor, and the virtualization is done within a single operating system, where the OS kernel allows for multiple isolated user space instances. The kernel is also responsible for sharing the system resources among instances and for limiting the impact of instances on each other.

This virtualization technique can be considered an evolution of the chroot mechanism in Unix systems. The chroot operation changes the file system root directory for a process and its children to a specific directory. As a result, the process and its children cannot have access to other portions of the file system than those accessible under the new root directory.

Examples of operating system-level virtualizations are FreeBSD Jails, IBM Logical Partition (LPAR), SolarisZones and Containers, Parallels Virtuozzo Containers, OpenVZ, iCore Virtual Accounts, Free Virtual Private Server (FreeVPS).

2.Programming language-level virtualization

Programming language-level virtualization is mostly used to achieve ease of deployment of applications, managed execution, and portability across different platforms and operating sys- tems. It consists of a virtual machine executing the byte code of a program, which is the result of the compilation process. Compilers implemented and used this technology to produce a binary format representing the machine code for an abstract architecture.

Programming language-level virtualization has a long trail in computer science history and originally was used in 1966 for the implementation of Basic Combined Programming Language (BCPL), a language for writing compilers and one of the ancestors of the C programming language.

Other important examples of the use of this technology have been the UCSD Pascal and Smalltalk.Virtual machine programming languages become popular again with Sun's introduction of the Javaplatform in 1996. Originally created as a platform for developing Internet applications, Java became one of the technologies of choice for enterprise applications, and a large community of developers formed around it. The Java virtual machine was originally designed for the execution of programs written in the Java language, but other languages such as Python, Pascal, Groovy, and Ruby were made available. The ability to support multiple programming languages has been one of the key elements of the Common Language Infrastructure (CLI),

3. Application-level virtualization

Application-level virtualization is a technique allowing applications to be run in runtime environments that do not natively support all the features required by such applications. In this scenario, applications are not installed in the expected runtime environment but are run as though they were.

Emulation can also be used to execute program binaries compiled for different hardware architectures. In this case, one of the following strategies can be implemented:

a. Interpretation. In this technique every source instruction is interpreted by an emulator for executing native ISA instructions, leading to poor performance. Interpretation has a minimal startup cost but a huge overhead, since each instruction is emulated.

b. Binary translation. In this technique every source instruction is converted to native instructions with equivalent functions. After a block of instructions is translated, it is cached and reused. Binary translation has a large initial overhead cost, but over time it is subject to better performance, since previously translated instruction blocks are directly executed.

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Other types of virtualization

Other than execution virtualization, other types of virtualization provide an abstract environment to interact with. These mainly cover storage, networking, and client/server interaction.

1 Storage virtualization

Storage virtualization is a system administration practice that allows decoupling the physical organization of the hardware from its logical representation. Using this technique, users do not have to be worried about the specific location of their data, which can be identified using a logical path. Storage virtualization allows us to harness a wide range of storage facilities and represent them under a single logical file system. There are different techniques for storage virtualization, one of the most popular being network-based virtualization by means of storage area networks (SANs).

2 Network virtualization

Network virtualization combines hardware appliances and specific software for the creation and management of a virtual network. Network virtualization can aggregate different physical networks into a single logical network (external network virtualization) or provide network-like functionality to an operating system partition (internal network virtualization). The result of external network virtualization is generally a virtual LAN (VLAN).

3 Desktop virtualization

Desktop virtualization abstracts the desktop environment available on a personal computer in order to provide access to it using a client/server approach. Desktop virtualization provides the same outcome of hardware virtualization but serves a different purpose. Similarly to hardware virtualization, desktop virtualization makes accessible a different system as though it were natively installed on the host, but this system is remotely stored on a different host and accessed through a network connection. Moreover, desktop virtualization addresses the problem of making the same desktop environment accessible from everywhere.

4 Application server virtualization

Application server virtualization abstracts a collection of application servers that provide the same services as a single virtual application server by using load-balancing strategies and providing a high-availability infrastructure for the services hosted in the application server. This is a particular form of virtualization and serves the same purpose of storage virtualization: providing a better qual- ity of service rather than emulating a different environment.

Virtualization and cloud computing

Virtualization plays an important role in cloud computing since it allows for the appropriate degree of customization, security, isolation, and manageability that are fundamental for delivering IT services on demand. Particularly important is the role of virtual computing environment and execution virtualization techniques. Among these, hardware and programming language virtualization are the techniques adopted in cloud computing systems.

Besides being an enabler for computation on demand, virtualization also gives the opportunity to design more efficient computing systems by means of consolidation, which is performed transparently to cloud computing service users.

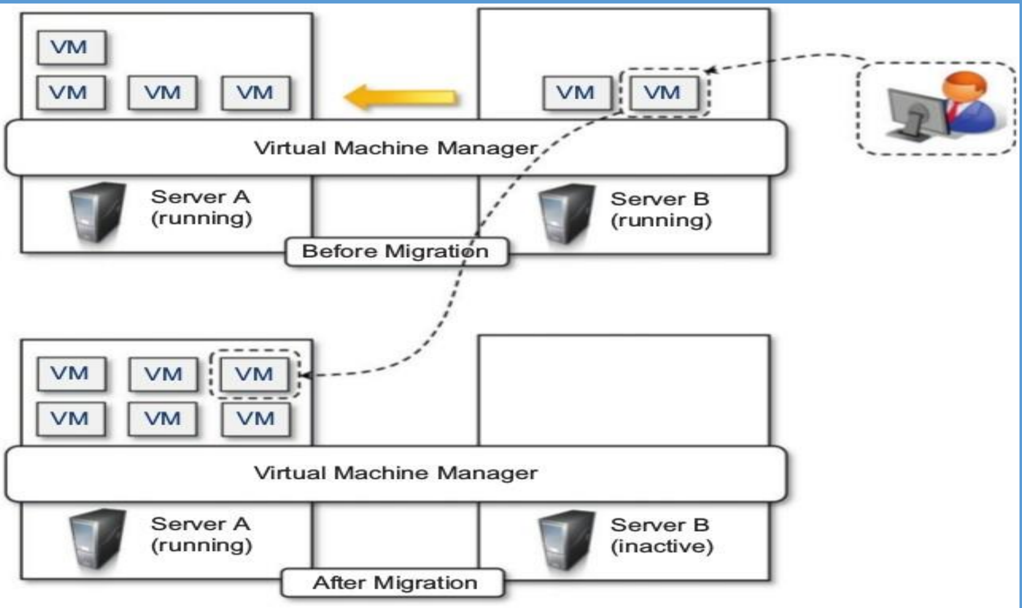

FIGURE 3.10

Live migration and server consolidation.

Since virtualization allows us to create isolated and controllable environments, it is possible to serve these environments with the same resource without them interfering with each other. This opportunity is particularly attractive when resources are underutilized, because it allows reducing the number of active resources by aggregating virtual machines over a smaller number of resources that become fully utilized. This practice is also known as server consolidation, while the movement of virtual machine instances is called virtual machine migration (see Figure 3.10). Because virtual machine instances are controllable environments, consolidation can be applied with a minimum impact, either by temporarily stopping its execution and moving its data to the new resources or by performing a finer control and moving the instance while it is running. This second techniques is known as live migration and in general is more complex to implement but more efficient since there is no disruption of the activity of the virtual machine instance.

Pros and cons of virtualization

Virtualization has now become extremely popular and widely used, especially in cloud computing. Today, the capillary diffusion of the Internet connection and the advancements in computing technology have made virtualization an interesting opportunity to deliver on-demand IT infrastructure and services.

Advantages of virtualization

1. Managed execution and isolation are perhaps the most important advantages of virtualization. In the case of techniques supporting the creation of virtualized execution environments, these two characteristics allow building secure and controllable computing environments.
2. Portability is another advantage of virtualization, especially for execution virtualization techniques. Virtual machine instances are normally represented by one or more files that can be easily transported with respect to physical systems.
3. Portability and self-containment also contribute to reducing the costs of maintenance, since the number of hosts is expected to be lower than the number of virtual machine instances. Since the guest program is executed in a virtual environment, there is very limited opportunity for the guest program to damage the underlying hardware.
4. Finally, by means of virtualization it is possible to achieve a more efficient use of resources. Multiple systems can securely coexist and share the resources of the underlying host, without interfering with each other.

The other side of the coin: disadvantages

1 Performance degradation

Performance is definitely one of the major concerns in using virtualization technology. Since virtualization interposes an abstraction layer between the guest and the host, the guest can experience increased latencies (delays).

For instance, in the case of hardware virtualization, where the intermediate emulates a bare machine on top of which an entire system can be installed, the causes of performance degradation can be traced back to the overhead introduced by the following activities:

- Maintaining the status of virtual processors
- Support of privileged instructions (trap and simulate privileged instructions)
- Support of paging within VM
- Console functions

2 Inefficiency and degraded user experience

Virtualization can sometime lead to an inefficient use of the host. In particular, some of the specific features of the host cannot be exposed by the abstraction layer and then become inaccessible. In the case of hardware virtualization, this could happen for device drivers: The virtual machine can sometime simply provide a default graphic card that maps only a subset of the features available in the host. In the case of programming-level virtual machines, some of the features of the underlying operating systems may become inaccessible unless specific libraries are used.

3 Security holes and new threats

Virtualization opens the door to a new and unexpected form of phishing. The capability of emulating a host in a completely transparent manner led the way to malicious programs that are designed to extract sensitive information from the guest.

The same considerations can be made for programming-level virtual machines: Modified ver- sions of the runtime environment can access sensitive information or monitor the memory locations utilized by guest applications while these are executed.

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IMP QUESTIONS

a) What is the innovative characteristic of cloud computing?
b) Which are the technologies on which cloud computing relies?
c) Provide a brief characterization of a distributed system
d) Define cloud computing and identify its core features.
e) What are the major distributed computing technologies that led to cloud computing?
f) What is virtualization?
g) What is the major revolution introduced by Web 2.0?
h) Write a note on service orientation.
i) What is utility computing?
j) Describe the vision introduced by cloud computing.
k) Briefly summarize the Cloud Computing Reference Model.
l) What is the major advantage of cloud computing?
m) Briefly summarize the challenges still open in cloud computing.
n) How is cloud development different from traditional software development
o) What is virtualization and what are its benefits?
p) What are the characteristics of virtualized environments?
q) Discuss classification or taxonomy of virtualization at different levels.
r) Discuss the machine reference model of execution virtualization.
s) What are hardware virtualization techniques?
t) List and discuss different types of virtualization.
u) What are the benefits of virtualization in the context of cloud computing?
v) What are the disadvantages of virtualization?
w) Discuss its use in cloud computing