4.4. TOOLS & MECHANISMS

Cloud computing tools and mechanisms enable flexible, on-demand infrastructure, with key technologies including hypervisors for virtualization, API-driven provisioning tools (e.g., AWS, Azure), and containerization (e.g., Docker, Kubernetes). Essential mechanisms, such as load balancers, auto-scaling listeners, and virtual storage, manage resource allocation, high availability, and scalability, supporting IaaS, PaaS, and SaaS models.

Key Cloud Computing Mechanisms

- **Hypervisor:** The fundamental technology for creating virtual machines (VMs), managing resource isolation, and controlling guest operating systems.
- **Virtualization (Types):** Includes Server (VMs), Storage (virtual disks), Network (Software-Defined Networking/SDN), and Desktop (virtualized user environments).
- **Load Balancer:** Distributes incoming traffic across multiple instances to optimize performance and prevent failure.
- **Automated Scaling Listener:** Monitors demand and triggers provisioning or de-provisioning of resources automatically.
- **Cloud Usage Monitor:** Tracks resource consumption for auditing, reporting, and billing (pay-per-use).
- **Resource Replication:** Creates identical instances of data or services to improve reliability.

Key Cloud Computing Tools

- **Infrastructure Platforms (CSPs):** Amazon Web Services (AWS), Microsoft Azure, Google Cloud Platform (GCP), Alibaba Cloud, and Oracle.
- **Provisioning & Infrastructure as Code (IaC):** Ansible, Terraform, Puppet, and Chef.
- **Containerization & Orchestration:** Docker and Kubernetes.
- **Management & Monitoring:** Cloud management tools that monitor security, cost, and compliance across multi-cloud environments.

Categories of Tools and Mechanisms

- **Infrastructure Components:** Virtual servers, virtual storage, and network interfaces.

- **Management Mechanisms:** Remote management interfaces, billing, and SLA monitors.
- **Security Mechanisms:** Encryption, firewalls, and Identity & Access Management (IAM

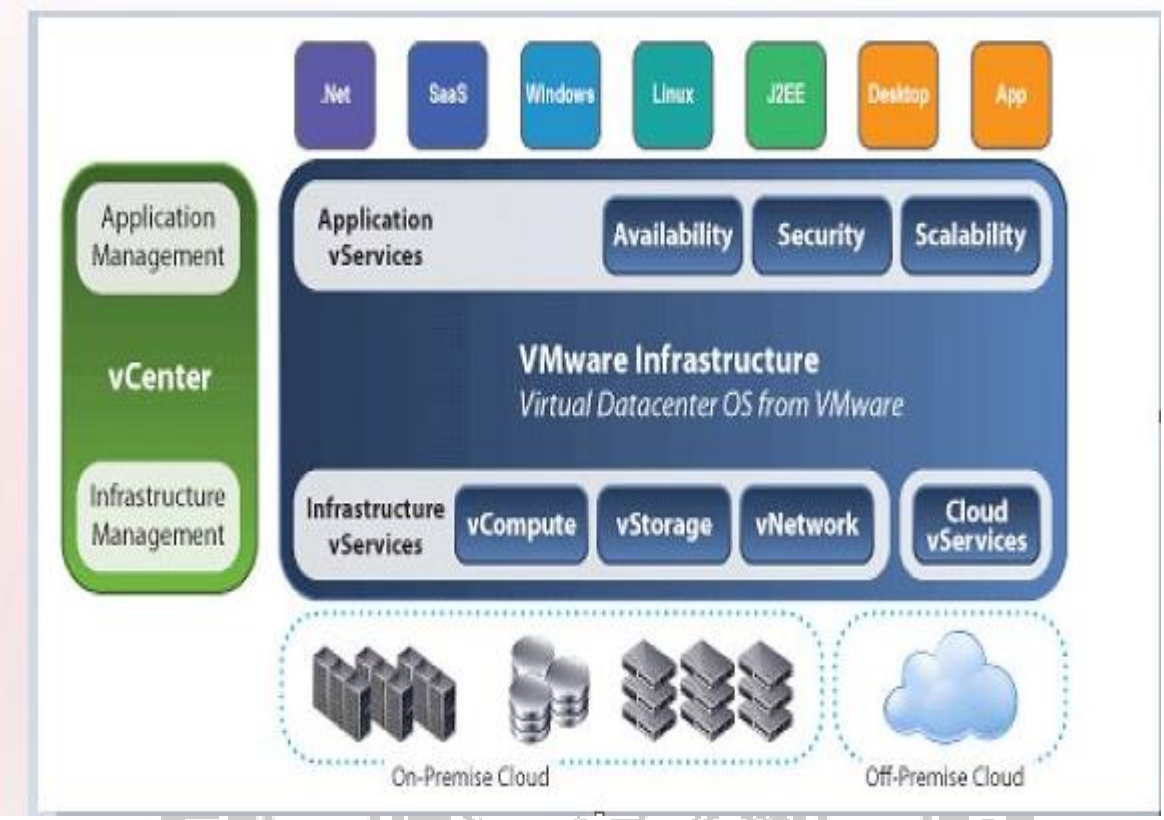
VIRTUALIZATION STRUCTURES/TOOLS AND MECHANISMS

In general, there are three typical classes of VM architecture. Figure 3.1 showed the architectures of a machine before and after virtualization. Before virtualization, the operating system manages the hardware.

After virtualization, a virtualization layer is inserted between the hardware and the operat-ing system. In such a case, the virtualization layer is responsible for converting portions of the real hardware into virtual hardware.

Therefore, different operating systems such as Linux and Windows can run on the same physical machine, simultaneously. Depending on the position of the virtualiza-tion layer, there are several classes of VM architectures, namely the hypervisor architecture, para-

virtualization, and host-based virtualization. The hypervisor is also known as the VMM (Virtual Machine Monitor). They both perform the same virtualization operations.



1. Hypervisor and Xen Architecture

The hypervisor supports hardware-level virtualization (see Figure 3.1(b)) on bare metal devices like CPU, memory, disk and network interfaces. The hypervisor software sits directly between the physi-cal hardware and its OS. This virtualization layer is referred to as either the VMM or the hypervisor. The hypervisor provides hypercalls for the guest OSes and applications. Depending on the functional-ity, a hypervisor can assume a micro-kernel architecture like the Microsoft Hyper-V. Or it can assume a monolithic hypervisor architecture like the VMware ESX for server virtualization.

A micro-kernel hypervisor includes only the basic and unchanging functions (such as physical memory management and processor scheduling). The device drivers and other changeable components are outside the hypervisor. A monolithic hypervisor implements all the aforementioned functions, including those of the device drivers. Therefore, the size of the hypervisor code of a micro-kernel hyper-visor is smaller than that of a monolithic hypervisor. Essentially, a hypervisor must be able to convert physical devices into virtual resources dedicated for the deployed VM to use.

1.1 The Xen Architecture

Xen is an open source hypervisor program developed by Cambridge University. Xen is a micro-kernel hypervisor, which separates the policy from the mechanism. The Xen hypervisor implements all the mechanisms, leaving the policy to be handled by Domain 0, as shown in Figure 3.5. Xen does not include any device drivers natively [7]. It just provides a mechanism by which a guest OS can have direct access to the physical devices. As a result, the size of the Xen hypervisor is kept rather small. Xen provides a virtual environment located between the hardware and the OS. A number of vendors are in the process of developing commercial Xen hypervisors, among them are Citrix XenServer [62] and Oracle VM [42].

The core components of a Xen system are the hypervisor, kernel, and applications. The organi-zation of the three components is important. Like other virtualization systems, many guest OSes can run on top of the hypervisor. However, not all guest OSes are created equal, and one in

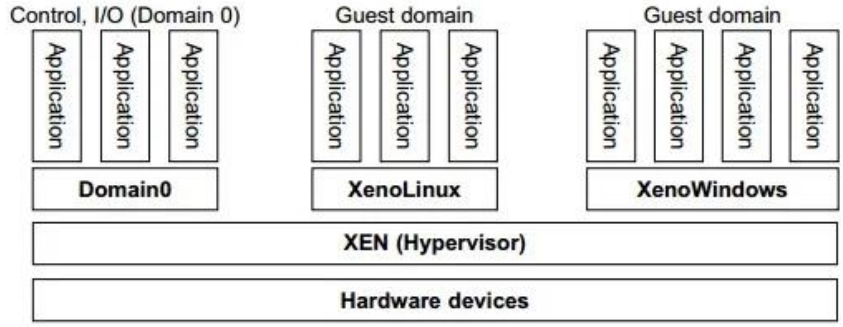


FIGURE 3.5
The Xen architecture's special domain 0 for control and I/O, and several guest domains for user applications.

2. Binary Translation with Full Virtualization

Depending on implementation technologies, hardware virtualization can be classified into two cate-gories: full virtualization and host-based virtualization. Full virtualization does not need to modify the host OS. It relies on binary translation to trap and to virtualize the execution of certain sensitive, nonvirtualizable instructions. The guest OSes and their applications consist of noncritical and critical instructions. In a host-based system, both a host OS and a guest OS are used. A virtuali-zation software layer is built between the host OS and guest OS. These two classes of VM architec-ture are introduced next.

2.1 Full Virtualization

With full virtualization, noncritical instructions run on the hardware directly while critical instructions are discovered and replaced with traps into the VMM to be emulated by software. Both the hypervisor and VMM approaches are considered full virtualization. Why are only critical instructions trapped into the

VMM? This is because binary translation can incur a large performance overhead. Noncritical instructions do not control hardware or threaten the security of the system, but critical instructions do. Therefore, running noncritical instructions on hardware not only can promote efficiency, but also can ensure system security.

2.2 Binary Translation of Guest OS Requests Using a VMM

This approach was implemented by VMware and many other software companies. As shown in Figure 3.6, VMware puts the VMM at Ring 0 and the guest OS at Ring 1. The VMM scans the instruction stream and identifies the privileged, control- and behavior-sensitive instructions. When these instructions are identified, they are trapped into the VMM, which emulates the behavior of these instructions. The method used in this emulation is called binary translation. Therefore, full vir-tualization combines binary translation and direct execution. The guest OS is completely decoupled from the underlying hardware. Consequently, the guest OS is unaware that it is being virtualized.

The performance of full virtualization may not be ideal, because it involves binary translation which is rather time-consuming. In particular, the full virtualization of I/O-intensive applications is a really a big challenge. Binary translation employs a code cache to store translated hot instructions to improve performance, but it increases the cost of memory usage. At the time of this writing, the performance of full virtualization on the x86 architecture is typically 80 percent to 97 percent that of the host machine.

2.3 Host-Based Virtualization

An alternative VM architecture is to install a virtualization layer on top of the host OS. This host OS is still responsible for managing the hardware. The guest OSes are installed and run on top of the virtualization layer. Dedicated applications may run on the VMs. Certainly, some other applications

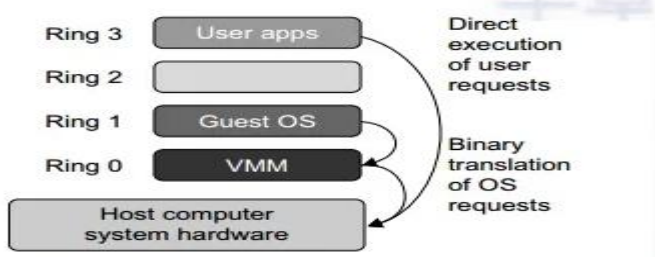


FIGURE 3.6
Indirect execution of complex instructions via binary translation of guest OS requests using the VMM plus direct execution of simple instructions on the same host.

can also run with the host OS directly. This host-based architecture has some distinct advantages, as enumerated next. First, the user can install this VM architecture without modifying the host OS. The virtualizing software can rely on the host OS to provide device drivers and other low-level services. This will simplify the VM design and ease its deployment.

3. Para-Virtualization with Compiler Support

Para-virtualization needs to modify the guest operating systems. A para-virtualized VM provides special APIs requiring substantial OS modifications in user applications. Performance degradation is a critical issue of a virtualized system. No one wants to use a VM if it is much slower than using a physical machine. The virtualization layer can be inserted at different positions in a machine soft-ware stack. However, para-virtualization attempts to reduce the virtualization overhead, and thus improve performance by modifying only the guest OS kernel.

Figure 3.7 illustrates the concept of a paravirtualized VM architecture. The guest operating systems are para-virtualized. They are assisted by an intelligent compiler to replace the nonvirtualizable OS instructions by hypercalls as illustrated in Figure 3.8. The traditional x86 processor offers four instruction execution rings: Rings 0, 1, 2, and 3. The lower the ring number, the higher the privilege of instruction being executed. The OS is responsible for managing the hardware and the privileged instructions to execute at Ring 0, while user-level applications run at Ring 3. The best example of para-virtualization is the KVM to be described below.

3.1 Para-Virtualization Architecture

When the x86 processor is virtualized, a virtualization layer is inserted between the hardware and the OS. According to the x86 ring definition, the virtualization layer should also be installed at Ring 0. Different instructions at Ring 0 may cause some problems. In Figure 3.8, we show that para-virtualization replaces nonvirtualizable instructions with hypercalls that communicate directly with the hypervisor or VMM. However, when the guest OS kernel is modified for virtualization, it can no longer run on the hardware directly.

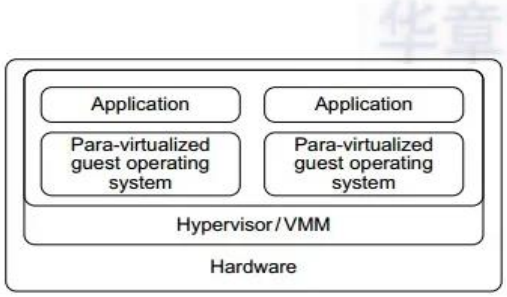


FIGURE 3.7

Para-virtualized VM architecture, which involves modifying the guest OS kernel to replace nonvirtualizable instructions with hypercalls for the hypervisor or the VMM to carry out the virtualization process (See Figure 3.8 for more details.)

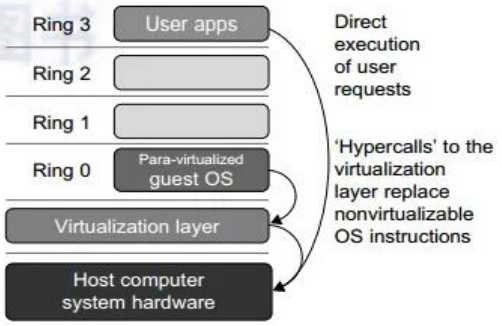


FIGURE 3.8

The use of a para-virtualized guest OS assisted by an intelligent compiler to replace nonvirtualizable OS instructions by hypercalls.

(*Courtesy of VMWare [71]*)

3.2 KVM (Kernel-Based VM)

This is a Linux para-virtualization system—a part of the Linux version 2.6.20 kernel. Memory management and scheduling activities are carried out by the existing Linux kernel. The KVM does the rest, which makes it simpler than the hypervisor that controls the entire machine. KVM is a hardware-assisted para-virtualization tool, which improves performance and supports unmodified guest OSes such as Windows, Linux, Solaris, and other UNIX variants.

3.3 Para-Virtualization with Compiler Support

Unlike the full virtualization architecture which intercepts and emulates privileged and sensitive instructions at runtime, para-virtualization handles these instructions at compile time. The guest OS kernel is modified to replace the privileged and sensitive instructions with hypercalls to the hypervi-sor or VMM. Xen assumes such a para-virtualization architecture.

The guest OS running in a guest domain may run at Ring 1 instead of at Ring 0. This implies that the guest OS may not be able to execute some privileged and sensitive instructions. The privileged instructions are implemented by hypercalls to the hypervisor. After replacing the instructions with hypercalls, the modified guest OS emulates the behavior of the original guest OS. On an UNIX system, a system call involves an interrupt or service routine. The hypercalls apply a dedicated service routine in Xen.

Example 3.3 VMware ESX Server for Para-Virtualization

VMware pioneered the software market for virtualization. The company has developed virtualization tools for desktop systems and servers as well as virtual infrastructure for large data centers. ESX is a VMM or a hypervisor for bare-metal x86 symmetric multiprocessing (SMP) servers. It accesses hardware

resources such as I/O directly and has complete resource management control. An ESX-enabled server consists of four components: a virtualization layer, a resource manager, hardware interface components, and a service console, as shown in Figure 3.9. To improve performance, the ESX server employs a para-virtualization architecture in which the VM kernel interacts directly with the hardware without involving the host OS.

The VMM layer virtualizes the physical hardware resources such as CPU, memory, network and disk controllers, and human interface devices. Every VM has its own set of virtual hardware resources. The resource manager allocates CPU, memory disk, and network bandwidth and maps them to the virtual hardware resource set of each VM created. Hardware interface components are the device drivers and the

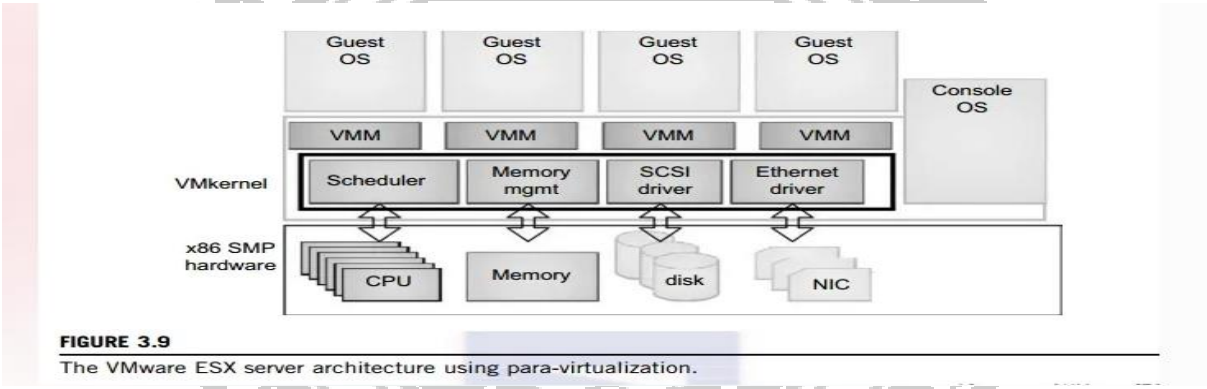


FIGURE 3.9
The VMware ESX server architecture using para-virtualization.

VMware ESX Server File System. The service console is responsible for booting the system, initiating the execution of the VMM and resource manager, and relinquishing control to those layers. It also facilitates the process for system administrators.